WORKING PAPER 59

The Lucille Mountain Study

8-year Results of a Silvicultural Systems Trial in the Engelmann Spruce–Subalpine Fir Zone

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The Lucille Mountain Study

8-year Results of a Silvicultural Systems Trial in the Engelmann Spruce–Subalpine Fir Zone

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Michael J. Jull and Susan K. Stevenson (editors)

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Prepared by

Michael J. Jull
University of Northern British Columbia
3333 University Way
Prince George, BC V2N 4Z9

and

Susan K. Stevenson
Silvifauna Research
101 Burden Street
Prince George, BC V2M 2G8

for

B.C. Ministry of Forests
Research Branch
712 Yates Street
Victoria, BC V8W 3E7

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LIST OF CONTRIBUTORS

S. Craig Delong, MSc, RPBio
Prince George Forest Region
1011 Fourth Avenue
Prince George, BC V2L 3H9

Andrea M. Eastham, MSc, PAg
Industrial Forestry Service Ltd.
1595 Fifth Avenue
Prince George, BC V2L 3L9

Michael J. Jull, MScF, RPF
University of Northern British Columbia
3333 University Way
Prince George, BC V2N 4Z9

Cleo C. Lajzerowicz, MSc
Industrial Forestry Service Ltd.
1595 Fifth Avenue
Prince George, BC V2L 3L9

Cynthia E. Prescott, PhD
Department of Forest Sciences
University of British Columbia
2424 Main Mall
Vancouver, BC V6T 1Z4

Robert M. Sagar, PhD
Box 25
Tatlayoko Lake, BC V0L 1W0

Paul Sanborn, PhD, PAg
Prince George Forest Region
1011 Fourth Avenue
Prince George, BC V2L 3H9

Susan K. Stevenson, MSc, RPBio
Silvifauna Research
101 Burden Street
Prince George, BC V2M 2G6

Michael Walters, PhD
126 Natural Resources Building
Michigan State University
East Lansing, MI 48824 U.S.A

ABSTRACT

The Lucille Mountain silvicultural systems project is a multi-disciplinary research trial that explores the effects of various harvest treatments on a stand in the moist mild Engelmann Spruce–Subalpine Fir subzone (ESSFmm). The trial, established in 1992, includes clearcut, patch cut, irregular shelterwood, group retention, and single-tree selection systems. Its initial focus was to evaluate the effectiveness of various silvicultural systems for achieving regeneration, but other research topics have been added. We present 8-year results of studies of the establishment and growth of planted seedlings, including investigations of the roles of light, soil temperature, and nitrogen availability. Studies of seed supply and the effects of seedbed condition on germination and survival have implications for the potential of natural regeneration to reforest the site. Growth and mortality in the residual stand after partial cutting at the individual-tree level and the stand level are reported. Taken together, these studies begin to elucidate complex relationships among the various components of the stand: the retained canopy trees, the vegetation community, and the natural, artificial, and advance regeneration.

Detailed climate studies provide additional baseline data for the ESSF, allow comparisons between conditions in the partial cuts and the clearcut, and provide background for interpretation of other studies. Since 1995, wind has also been monitored, along with wind damage in the partial cuts and adjacent to the clearcut. Other investigations reported here include the effects of partial cutting on the abundance and growth rates of arboreal lichens used by mountain caribou, and decomposition rates of forest floor litter.

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Marty Osberg
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Dave (Buck) Tanner

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The Lucille Mountain ESSF silvicultural systems project is a multi-disciplinary research trial that explores the effects of different silvicultural system treatments and harvesting patterns on high-elevation Engelmann Spruce–Subalpine Fir (ESSF) forests. The trial, which was established in 1992, examines a spectrum of uneven-aged and even-aged stand management strategies on a mesic site in the moist mild Engelmann Spruce–Subalpine Fir subzone (ESSFmm) (B.C. Ministry of Forests 1996) near McBride, B.C. (Figure 1). Silvicultural systems implemented at this site include clearcut, patch cut, irregular shelterwood, group retention, and single-tree selection systems. The duration of the trial is planned to be one rotation (about 100–120 years). The trial is designed not only to provide forest managers and researchers with short-term and medium-term results, but also to provide insights into long-term treatment effects.

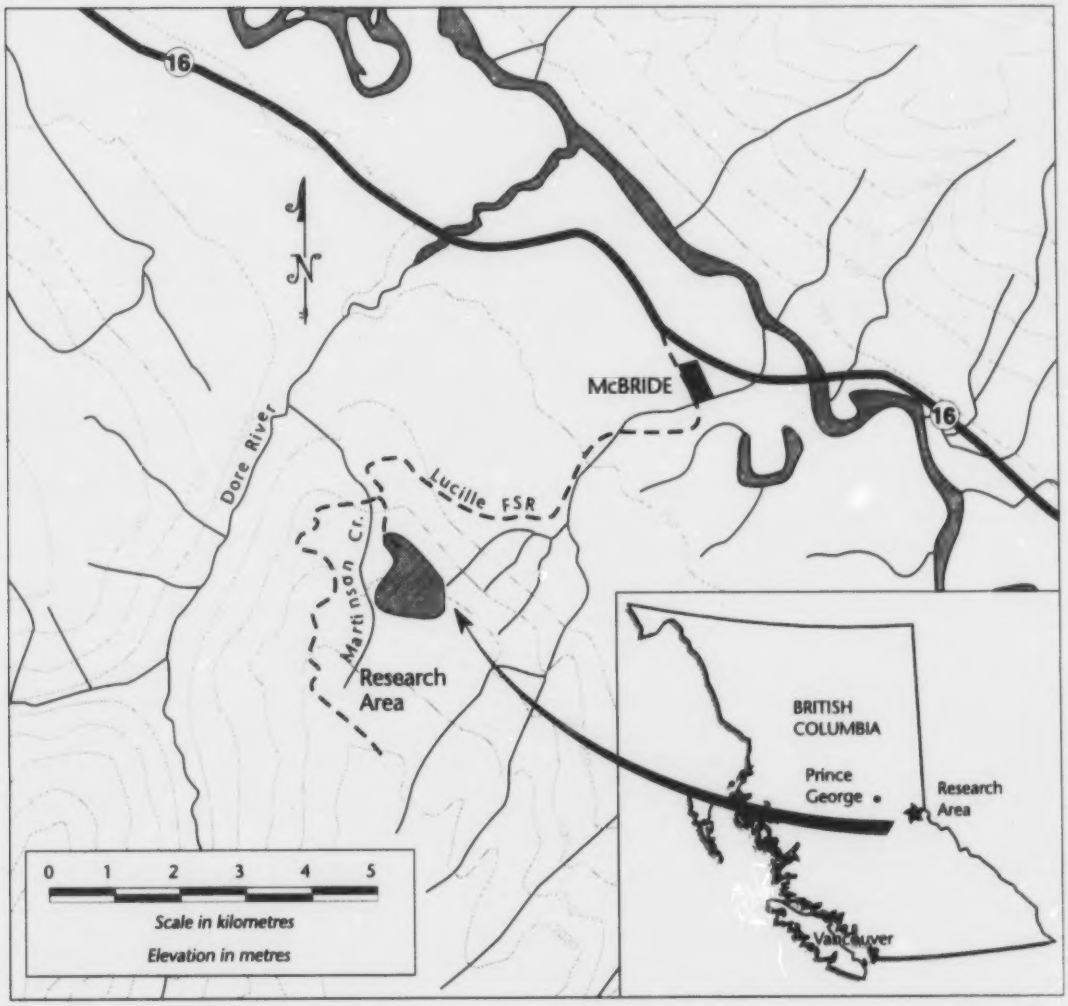

FIGURE 1 *Location of the Lucille Mountain silvicultural systems research site.*

Treatment response variables examined at Lucille Mountain include:

- microclimate;
- understorey plant succession;
- vegetation competition;
- regeneration establishment, growth rate, vigour, and species composition; limiting ecological factors to performance of planted regeneration;
- wind damage to partial cut stands and clearcut edges relative to high-wind events;
- arboreal lichen abundance and production; and
- rates of organic matter decomposition.

The Lucille Mountain Project (EP 1119) (DeLong et al. 1991) is one of three ESSF silvicultural system research projects in central and south-central British Columbia. The others include the Grain Creek – Blackbear Creek group selection trials in the Cariboo Forest Region (EP 1104.02) (B.C. Ministry of Forests 1992), and the Sicamous Creek silvicultural systems trial in the Kamloops Forest Region (Hollstedt and Vyse 1997). The three trials are similar in general objectives and approach, and will provide scientific information on management of ESSF silvicultural systems in British Columbia. The Lucille Mountain Project will also provide information that is locally applicable to the northern Rocky Mountains and Cariboo/Columbia mountain ranges.

This report describes and synthesizes the results to date of the studies at Lucille Mountain. It is intended to provide forest managers and practitioners with key results and management implications. It also provides research scientists with a general overview of the project, and references to publications and reports in which more detailed research results may be found.

2 BACKGROUND AND RATIONALE

2.1 Extent and Significance of ESSF Zone Forests

The Engelmann Spruce–Subalpine Fir zone is one of the most extensive forest zones in British Columbia. It includes some of the province's most severe climates for forest growth. At higher elevations, this forested zone of Engelmann spruce (*Picea engelmannii* (Parry) Engelm.) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) grades into the subalpine parkland and alpine tundra. These forests are frequently important for wildlife habitat, mountain recreation, scenic values, and other resource values. They influence snowmelt and water flows in many watersheds, and have substantial timber values for the forest industry.

The ESSF zone covers 14.4 million hectares, or 15% of British Columbia's land area (B.C. Ministry of Forests 1998). In the Prince George Region and elsewhere in interior British Columbia, the extensive mature forests in the ESSF zone are an important part of the present timber harvesting land base. For example, the ESSF zone accounts for about 50% of the productive forest land base in the Robson Valley Forest District, and about 10% in the Prince George Forest District. However, because these forests are slow-growing and are important for many different resource values, the design of ESSF silvicultural systems must consider the limitations of subalpine growing conditions, diverse management objectives, and the sensitive nature of these ecosystems.

Subalpine forest sites are frequently characterized as limiting, relatively marginal environments for tree growth, especially regeneration (Tranquillini 1979; Smith 1985; Waring 1985). Vyse (1997) observes that, because subalpine forests have a visible limit (i.e., the tree line), the ESSF zone and subalpine spruce-fir forests in general are perceived to be at the "physiological edge" of forest growth and survival. It is often presumed that timber harvesting treatments involving extensive removal of the existing forest cover (e.g., clearcutting) and microclimatic shelter of that forest cover will carry with them a high risk of regeneration failure and very slow recovery. Paradoxically, however, as Vyse points out, there are numerous examples of successful management of subalpine forests throughout North America and Europe, many of which include some use of clearcut systems.

2.2 History of ESSF Forest Management

For the last three decades, clearcutting has been the dominant harvesting method and silvicultural system used in ESSF forests. Typical reasons given for the widespread use of clearcut systems in subalpine ESSF forests include the following (adapted from DeLong et al. 1991):

1. economic efficiency for short-term harvesting and silvicultural operations;
2. high timber revenues, in part to offset the high cost of road access in difficult mountainous terrain;
3. removal of shade to warm the soil and speed establishment of planted regeneration;
4. facilitation of slash disposal for easy planter access and pest management;
5. replacement of old mixed stands of subalpine fir and spruce with young even-aged plantations of the more commercially desirable Engelmann spruce; and
6. negative attitudes toward partial cutting, based on a legacy of "diameter-limit" logging that included high-grading of large spruce trees, high rates of logging damage to leave-trees, and windthrow losses.

Historically, the creation of large clearcuts in the ESSF zone often resulted in regeneration failure (Mather 1987; Butt 1990; Farnden 1994; Vyse 1997). More recently, most regeneration problems in ESSF clearcuts have been solved through improved silvicultural practices, including improved site preparation choices, nursery culture, and stock type selection, and prompt planting of harvested areas (Farnden 1994; Vyse 1997; Lajzerowicz 2000).

In the last 15 years, however, public attitudes have become increasingly critical of clearcut harvesting practices and their impacts on many non-timber forest resources, such as scenic areas, caribou habitat, biodiversity, and recreation. As a result, since the start of the Lucille Mountain Project in the late 1980s, British Columbia has undergone a rapid evolution in forest policies and practices. One major legislative change has been the *Forest Practices Code of British Columbia Act*, passed in 1995. Land use planning processes, such as Land and Resource Management Plans (LRMPs), have incorporated many public concerns, and have identified many sensitive areas in the forest harvesting land base where non-timber forest resources have equal or greater emphasis than traditional timber management objectives. In general, in the ESSF zone and many other forest types, the public increasingly expects to see a range of silvicultural systems used to meet

diverse resource management objectives (Farnden 1994; Vyse 1997). In many visually sensitive areas and some wildlife habitats in British Columbia, partial cut silvicultural systems are increasingly being seen as the lowest-impact, and therefore most desirable, forest management option. In some cases, such as critical mountain caribou ranges, low-removal partial cut systems are the only silvicultural systems considered acceptable to maintain habitat values (Armleder and Stevenson 1995).

Use of partial cut silvicultural systems has often been hindered by a lack of operational experience with related harvesting practices. In addition, there is a lack of knowledge and much uncertainty about silvicultural and ecosystem response to various stand management options. For example, there is continuing disagreement about the advantages and disadvantages of leaving advance regeneration and large residual trees on site after harvesting in the ESSF zone. Some forest managers see the destruction of residual trees during clearcut harvesting as an unnecessary loss of established growing stock. Others see the removal of the old stand as being a necessary step for establishment of vigorous even-aged plantations. From still another perspective, retention of forest cover on ESSF sites after harvesting is increasingly seen as an important part of managing these forests for visual quality, wildlife habitat, and other non-timber objectives.

Well-designed and well-monitored research trials play an important role in testing and comparing various management options, and providing information on treatment results. The choice and successful application of different silvicultural systems in ESSF forests will be greatly aided by improved scientific understanding of subalpine forest ecosystems, and the response of these ecosystems to different silvicultural treatments.

2.3 Research and Adaptive Management in ESSF Forests

Rapid development of ecologically appropriate silvicultural systems in the ESSF zone requires a change from historical patterns of "trial-and-error" in British Columbia forest management. Historically, the driving forces for changes in harvesting and regeneration methods have often been economic or administrative pressures. Biological rationales have been a secondary consideration. Some operational attempts at partial cutting in spruce-fir types in British Columbia in the 1950s and 1960s were unsuccessful and yielded little long-term information due to poor planning, inadequate or non-existent documentation, and little or no long-term monitoring of results (Glew 1963; Weetman and Vyse 1990; Weetman 1996).

The risks of traditional operational trial-and-error approaches are potentially high. In harsh ecosystems such as the ESSF, ecosystem responses to forest practices are slow. The results of poorly chosen forest practices may take a long time to become evident, by which time corrective measures may be difficult or impossible. The cumulative result can be a forest land base widely dominated by unanticipated silvicultural mistakes. Trial-and-error approaches assume that the public and resource managers have a high tolerance for many such mistakes. Increasingly, this assumption is being found to be incorrect. Alternatives to trial-and-error for testing management concepts include retrospective approaches (Oliver and Larson 1982) and chronosequence approaches (Pickett 1987). However, these and related approaches have only limited ability to contribute to increased ecological understanding of ecosystem dynamics in response to disturbance. Such limitations may include a narrow range of available treatments, poorly

quantified treatments, lack of known or documented initial conditions, and inability to examine individual processes contributing to a treatment response or outcome.

An alternative to trial-and-error, retrospective, and chronosequence approaches is adaptive management (Nyberg 1998). Adaptive management tests management strategies through careful planning, implementation, monitoring, and comparison of different treatments on a limited area of the land base. Key assumptions of different forest management strategies are tested and validated through scientific study of underlying physical and ecological processes. This approach gives managers a robust scientific assessment of various forest management options, based on ecological foundations. The Lucille Mountain Project has functioned as a starting point for an adaptive management process that has extended beyond the east-central interior; lessons from Lucille Mountain have been incorporated into other research installations and into operational management trials.

3 STUDY OBJECTIVES

The original objective of the Lucille Mountain study was " . . . to evaluate and contrast the biological implications of implementing partial cut silvicultural systems with those of clearcutting in the ESSFmm" (DeLong et al. 1991). Although the primary objective was stated broadly, and the study site was selected because of public concerns about the potential impact of clearcutting on water quality and aesthetic values, research plans focused on evaluating the effectiveness of various alternative silvicultural systems for achieving regeneration. These plans were shaped by several different "working hypotheses" that guided thinking about high-elevation silviculture in the mid- to late 1980s, when the project was conceived. Some of these competing ideas were:

- Regeneration establishment in ESSF forests is limited by frost.
- Regeneration establishment in ESSF forests is limited by soil temperature.
- Regeneration establishment in ESSF forests is limited by vegetation competition.
- Engelmann spruce is more productive and produces higher-quality wood than subalpine fir in the ESSF.
- Artificial regeneration is a more reliable as a regeneration strategy than natural regeneration or release of advanced regeneration in the ESSF.
- Mature trees in the residual stand, especially subalpine fir, do not respond well to release by partial cutting in the ESSF.
- The risk of windthrow after partial cutting in the ESSF is high.

Most of the research under way at Lucille Mountain has been designed to test these ideas. As well, some researchers have used the study area to address other questions.

The overall objective of the Lucille Mountain Project, as it exists today, is to compare and contrast the effects of various stand structures and silvicultural systems in the ESSFmm subzone on forest vegetation and climate, and to identify the management implications of these effects.

Specifically, the research addresses the effects of a range of even-aged and uneven-aged silvicultural systems on:

1. near-ground microclimate, including soil temperature, air temperature, and light;
2. changes in the vegetation community over time;
3. the production of viable seeds and the distribution of seed rain;
4. the influence of seedbed and seed supply on germination frequency, density, and survival of Engelmann spruce and subalpine fir;
5. changes over time in vegetation that potentially competes with planted seedlings for light;
6. survival, aboveground and belowground growth, ecophysiological responses, and limiting factors to growth of planted Engelmann spruce and subalpine fir seedlings;
7. post-harvest survival, growth response, and mortality of the various size classes of Engelmann spruce and subalpine fir residual trees;
8. the response of the residual stand and clearcut edges to the incidence and severity of high-wind events;
9. the abundance and growth rates of the arboreal lichens *Alectoria sarmentosa* and *Bryoria* spp. in the lower canopy of residual trees; and
10. rates of organic matter decomposition on the forest floor.

4 SITE DESCRIPTION

The study site is located on a northwest-facing slope on Lucille Mountain, southwest of McBride (Figure 1), in the ESSFmm1 variant. The elevational range is 1340–1585 m (4400–5200 feet) above sea level. Slopes range from about 15–45%, and average 30–35%. The ecosystem units treated in this trial are generally mesic. Soils are predominantly Humo-Ferric Podzols with a silty texture, formed on a blanket of medium- to coarse-textured morainal deposits. Appendix 1 provides a more detailed description of Lucille Mountain soils.

The stands within and around the study site are typical of unlogged mature Engelmann spruce–subalpine fir stands in the region. The understorey is dominated by shrubs such as *Rhododendron albiflorum*, *Vaccinium membranaceum*, *V. ovalifolium*, and *Menziesii ferruginea*, and herbs such as *Rubus pedatus* and *Streptopus roseus*. The moss layer is dominated by the moss *Pleurozium schreberi* and the liverwort *Barbilophozia lycopodioides*. The arboreal lichens *Bryoria* spp. (especially *B. glabra*, *B. fuscescens*, *B. pseudofuscescens*, and *B. fremontii*) and *Alectoria sarmentosa* are moderately abundant, and are significant winter forage for the mountain caribou that range in the area.

The pre-harvest stand at Lucille Mountain was dominated by subalpine fir, with a smaller component of Engelmann spruce, in all canopy layers (Table 1). The tallest spruce were typically 25–35 m, while the tallest subalpine fir were 22–30 m. The diameter class structure of the pre-harvest stand displayed a negative exponential ("inverse J-shaped") curve typical of many uneven-aged stands (Figure 2). Basal area was 31.5 m^2/ha. Merchantable volume was 220.9 m^3/ha, of which 78% was subalpine fir and the remainder spruce. Of the 500 stems/ha >17.5 cm diameter at breast height

(dbh), 103 (20.6%) were non-merchantable standing dead trees, classified as "dead useless" in the timber cruise. Most standing dead trees (93.3%) were subalpine fir.

Available age information indicates that the pre-harvest stand was generally uneven-aged as well as uneven-sized, and may have developed for four to five centuries since the last major stand-destroying disturbance. Ages of spruce ≥1.3 m high ranged from 29 to a maximum of 455 years, while subalpine fir ≥1.3 m ranged from 35 to 430 years (K. Simonar in Audet 1992, p.29). Overall, subalpine fir is the shorter-lived species at an average pre-

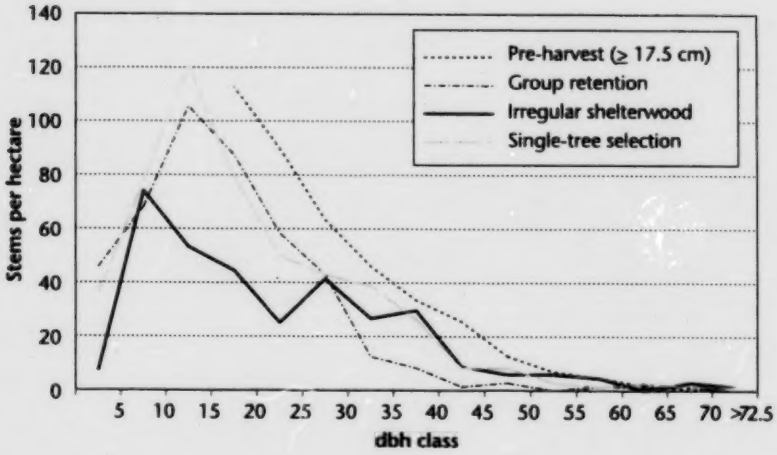

FIGURE 2 *Pre-harvest diameter distribution in the 15-ha partial cutting area and post-harvest diameter distribution in the three partially cut treatment units.*

TABLE 1 *Pre-harvest stand and stock tables by species, from August 1988 cruise compilation*

	Stems/ha		Merchantable volume (m^3/ha)	
dbh class midpoint	Spruce	Subalpine fir	Spruce	Subalpine fir
20	10.7	100.9	1.4	14.8
25	3.1	86.7	0.7	24.8
30	4.6	58.8	2.0	28.3
35	1.4	44.3	1.1	28.8
40	5.4	27.8	5.7	25.8
45	4.2	21.4	6.0	25.6
50	4.4	8.3	7.6	12.3
55	2.6	4.4	5.7	7.4
60	2.7	1.4	7.7	3.0
65	1.4	0.4	4.0	1.0
70	0.4	0.0	1.5	0.0
75	0.7	0.0	2.9	0.0
80	0.4	0.0	1.7	0.0
85	0.3	0.0	1.1	0.0
Total	42.3	354.4	49.1	171.8
%	10.7%	89.3%	22.2%	77.8%

harvest age of 174 years, while the average age of spruce was 218 years.

Based on pre-harvest annual ring profiles developed by Audet (1992), the typical age range of canopy trees was 100–260 years, with several periods of growth release required to reach the canopy. More than 90% of germinants and saplings occurred on nurse logs or apparent old root mounds. Initial tree growth in the uncut stand was very slow, with average years to reach 1.3 m breast height of 57 years (range 29–125 years) for subalpine fir and 35 years (range 18–82 years) for spruce.

On this generally mesic ESSFmm site, SIBEC site index (SI_{50}, based on a reference age of 50 years) for both Engelmann spruce and subalpine fir is estimated to be 15 m (B.C. Ministry of Forests 1997). Alternative methods for determination of ESSF site indices (Klinka et al. 1996) are based on relationships developed between SI_{50} of fire-origin stands and average elevation and latitude. The methods of Klinka et al. (1996) result in an SI_{50} for the Lucille Mountain research site (1350–1550 m; 53° 15' N) of 9.8–12.7 m for Engelmann spruce and 9.6–11.6 m for subalpine fir.

The climate is generally moist and cool throughout the growing season on this northern aspect. Growing-season frosts are not frequent due to the sloping nature of the site. In general, the ESSF zone has a cold, wet, and snowy continental climate (Coupé et al. 1991; Reynolds 1997). In wetter ESSF subzones, growing seasons are cool and short (typically a frost-free period of 48–100 days) while winters are long and cold. Mean annual temperature ranges from -3 to +2° C. Mean monthly temperatures are below 0° C for 5–7 months. Mean monthly temperatures rise above 10° C for about 1–2 months. Mean annual precipitation is high but varies with topography and elevation, ranging from 1050 to 2100 mm per year. Most (60–80%) falls as snow. Snowpacks develop in about mid-October and last to mid-June in most years. Snow depth typically reaches 2–3 m by late winter.

Results of climate studies at Lucille Mountain are given in Section 6.1.

The study site was originally selected to address public concerns in the area about the impact of clearcut harvesting on biodiversity, aesthetic values, recreational values, and watershed values in the area. The study site is visible from the town of McBride and nearby areas in the Rocky Mountain Trench. Lucille Mountain and adjacent Bell Mountain are used extensively for summer and winter outdoor recreation. The study site lies within a Caribou Medium Priority wildlife management zone designated by the Ministry of the Environment. The area has a "preservation" Visual Quality Objective (VQO), as designated by the Robson Valley Forest District. The study site is partially within an eastern portion of the Martinson Creek watershed, and adjacent to the McBride municipal watershed.

The treatments included in the Lucille Mountain research project were designed to create a wide range of even-aged and uneven-aged stand conditions. Silvicultural treatments used at this site include clearcut, patch cut, irregular shelterwood, group retention, and single-tree selection systems. These five treatment types are illustrated in Figure 3 and summarized in Table 2.

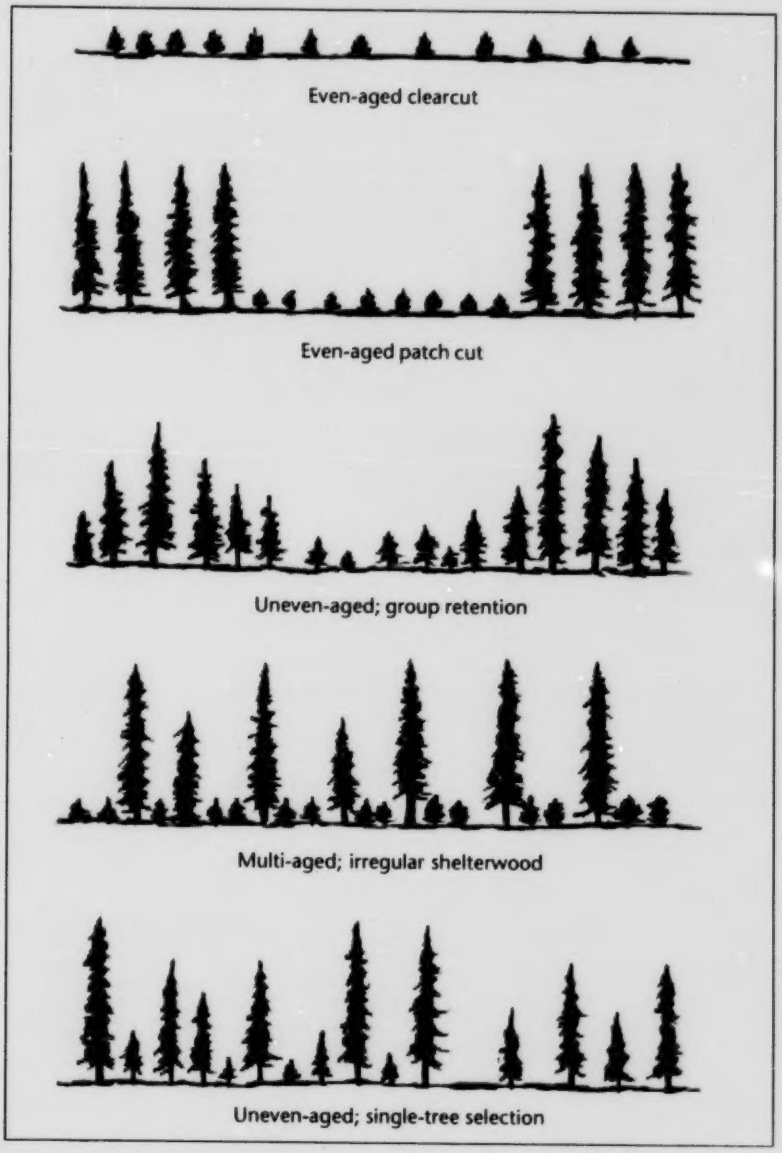

FIGURE 3 *Stand structures resulting from the harvest treatments used at Lucille Mountain.*

The treatment descriptions used in this Working Paper reflect accepted silvicultural systems terminology (B.C. Ministry of Forests 1995a). The terms chosen for each treatment are simply a "best fit" of existing terms for describing each stand structural goal in terms of spatial distribution of leave-trees in the stand, and the planned stand development over time. For greater detail, refer to the treatment descriptions in the following sections.

The block was harvested under the B.C. Ministry of Forests Small Business Forest Enterprise Program (Timber Sale Licence A33976) in 1991 and 1992. The layout of the treatment units is shown in Figure 4. The layout reflects the size of the study area, which precluded large replicated treatment units, and the focus of the project on relationships between stand structure and conifer regeneration.

5.1 Clearcut Treatment

For the clearcut (CC) treatment, the pre-existing mature stand was completely removed by timber harvesting, and even-aged regeneration established after harvest by planting. In the clearcut, the regeneration has relatively uniform species composition and spacing compared to the original old-growth stand (Figure 3). The primary species planted was Engelmann spruce, with mixed planting of spruce and subalpine fir on research plots. The stand structure goal for the clearcut system is an even-aged plantation of Engelmann spruce.

The clearcut unit was logged over two seasons, in summer and fall 1991 and summer 1992. The clearcut treatment area was hand-felled, and rubber-tired (wheeled) skidders were used to skid the wood tree-length to landings. Summer harvesting with rubber-tired skidders destroyed most of the existing advance regeneration. Less than one-quarter of pre-harvest advance regeneration survived the logging in any condition. Post-harvest sunscald, logging injury, and post-harvest stresses resulted in additional high mortality of advance regeneration.

The clearcut treatment was not site-prepared after harvest. Approximately 4 ha of the clearcut were summer-planted in late July and early August 1992.

TABLE 2 *Summary of treatments at the Lucille Mountain silvicultural systems research site*

Treatment	Stand structure	Year of harvest	Season of harvest	Opening size	Elevation	Harvest removal
Clearcut (CC)	Even-aged	1991/2	Summer/fall	32 ha	1425–1585 m	100%
Patch cut –summer (PCS)	Even-aged	Sept. 1991	Summer/fall	0.2 ha	1340–1445 m	50% by area
Patch cut –winter (PCW)	Even-aged	Feb. 1992	Winter on 1-m snowpack	0.2 ha	1340–1445 m	50% by area
Group retention (GR)	Clumpy uneven-aged	Feb. 1992	Winter on 1-m snowpack	Variable .01–0.1 ha	1425–1550 m	69% of basal area
Irregular shelterwood (IS)	Two-aged	Feb. 1992	Winter on 1-m snowpack	n/a	1425–1550 m	50% of basal area
Single-tree selection (ST)	Uniform uneven-aged	Feb. 1992	Winter on 1-m snowpack	n/a	1425–1550 m	49% of basal area

This included five 40 × 40 m research plots, which were planted with rows of summer-lifted subalpine fir (seed lot 3716) and Engelmann spruce (seed lot 8583). The subalpine fir were grown for 2 years in Styroblock containers (PSB 415B 105 ml volume; Beaver Plastics, Edmonton, Alta.), and then transplanted and grown for a year in a nursery bed, to produce a 3-year-old (2+1) plug-transplant (PBR) stock type. The spruce were grown for 2 years (2+0) in Styroblock containers (PSB 313B 90 ml volume). Thirty-metre-wide buffer areas around the research plots were planted at the same time with 2+0 spruce at 2.5-m spacing, or 1600 stems per hectare (sph). The remainder of the 32-ha block was spring-planted in June 1994, with 1600 sph of 1-year-old (1+0) PSB 415B Engelmann spruce seedlings.

5.2 Patch Cut Treatment

For the patch cut (PC) treatment, 14 patch cuts were harvested. Most openings were 0.2 ha (approximately 45 × 45 m), but a few of the openings along the edges of the treatment area were smaller. The patch cuts covered about 50% of the total treatment area, resulting in a "checkerboard" pattern of patch

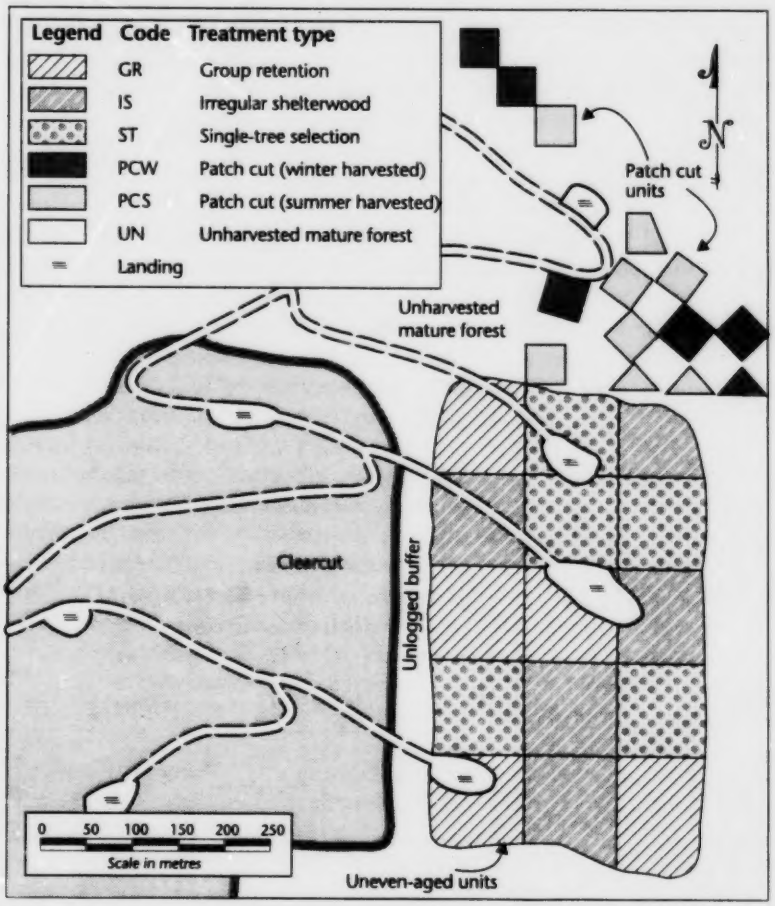

FIGURE 4 *Layout of the harvest treatment units at the Lucille Mountain silviculture systems research site.*

cut and uncut retention areas. The patch cuts are slightly less than two mature tree lengths wide. Regeneration within individual patch cuts will be even-aged.

Of the 14 patch cuts, eight were harvested on bare ground or light snow in September 1991, while six were winter-logged on a snowpack of 1 m or more in February 1992. The layout of summer patch cuts (PCSs) and winter patch cuts (PCWs) is shown in Figure 4. The harvest method was hand-falling, and rubber-tired skidders were used to move the trees to landings.

Four of the summer-logged patch cuts were raw-planted in July 1992, with an equal number of rows of subalpine fir and Engelmann spruce in each patch cut. Seed lots and stock types were identical to those used for research plots in the clearcut, as described above. Four of the summer-logged patch cuts were not planted, and will continue to rely on natural regeneration seeding-in from the adjacent uncut stand. The winter-logged patch cuts were also left unplanted.

Within the patch cuts, three different even-aged regeneration methods are being compared:

1. natural regeneration of spruce and subalpine fir from seed (summer-harvested patch cuts);
2. planted regeneration of spruce and subalpine fir (summer-harvested patch cuts); and
3. retention of advance regeneration (patch cuts winter-harvested on deep snowpack).

5.3 Partial Cut Treatments

The overall intent of the three partial cut treatments is to create and maintain two-aged or multi-aged stand structures. In these partial cuts, the harvest removals were dispersed more or less uniformly throughout the treatment units. These partial cut treatments include group retention (GR), irregular shelterwood (IS), and single-tree selection (ST) treatments. Each of these three treatments was replicated five times in a 3 × 5 randomized complete block design (Figure 4). The area of each treatment replicate was 1 ha. The total area of the 3 × 5 block design is 15 ha. A 40-m uncut buffer strip was left between the clearcut and the partial cut treatments to minimize direct wind exposure and microclimatic influence of the clearcut on the partially cut stand.

A common objective in all the partial cut treatments was the retention of about 50% of the pre-harvest volume and basal area. Actual levels achieved are shown in Table 3. The stands were marked-to-leave to meet desired stand

TABLE 3 *Mean basal area and volume of live trees in the partial cut treatment areas*

Silvicultural system	Stand parameter	Pre-harvest	Post-harvest	Amount removed	Removal
Group retention (GR)	Basal area (m^2)	32.4	10.0	22.4	69%
	Volume (m^3)	249.0	78.0	171.0	69%
Irregular shelterwood (IS)	Basal area (m^2)	29.9	14.9	15.0	50%
	Volume (m^3)	239.0	128.0	111.0	47%
Single-tree selection (ST)	Basal area (m^2)	32.3	16.4	15.9	49%
	Volume (m^3)	248.0	133.0	115.0	44%

structure and volume removal objectives, while retaining trees of above-average quality and maintaining the pre-harvest species composition. The treatment units were logged in February 1992, on 1–2 m of snowpack. The harvest method was hand-falling and ground-skidding of tree-length logs with Caterpillar D4H Hi-drive crawler-tractors with 30-inch (72.6-cm) tracks. Snags were felled to comply with Workers' Compensation Board regulations.

In addition to stems felled during harvest activities, trees less than 20–25 cm dbh that had been severely damaged during logging were felled in summer 1992. This was an operational measure in all partial cut treatments to improve the general quality of the residual stand.

Detailed discussion of the individual partial cut treatments is provided in Sections 5.3.1–5.3.3. A comparison of post-harvest residual stand diameter distributions resulting from the different harvesting patterns and silvicultural systems is provided in Figure 2 and Appendix 2.

5.3.1 **Group retention** The intent of the group retention (GR) treatment was to maintain the clumpy, heterogeneous uneven-aged stand structure observed in many ESSF forests at higher elevations (Table 2; Figure 3). Natural groups containing predominantly thrifty mature trees, poles, and advance regeneration were marked for retention. Planned volume and basal area removal was 50%. However, actual mean removal of both basal area and volume was 69%. The difference between planned and actual removal levels occurred because groups of older mature trees to be harvested had a higher average height, volume, and basal area than groups with equivalent numbers of mid-sized and smaller trees that were marked-to-leave.

Half the area of each group retention treatment unit was raw-planted in June 1995, with about 450 sph of Engelmann spruce 1+0 PSB 415B stock type (seed lot 10185). Seedlings were planted at a minimum spacing of 1 m from surrounding established trees, and at an average spacing of 2 m, depending on availability of microsites. The other half of each treatment unit was left unplanted to provide long-term comparisons between naturally regenerated and planted areas.

5.3.2 **Irregular shelterwood** The intent of the irregular shelterwood (IS) treatment was to create a two-aged stand structure by retaining a uniformly distributed overstorey of co-dominant and dominant trees, and protecting the understorey of advance and planted regeneration. (Table 2; Figure 3). Most of the intermediate diameter classes were harvested. Removal of the intermediate size classes is intended to aid the establishment of a planted spruce regeneration layer under the residual overstorey, and thereby increase the spruce component of the regeneration layers. Smaller subalpine fir and spruce advance regeneration in the stand were protected during harvesting by a deep snowpack.

In summer 1992, five 40 × 40 m research plots, one in each of the five 1-ha treatment replicates, were raw-planted with alternate rows of Engelmann spruce and subalpine fir seedlings.

In the remainder of the treatment unit, half the area of each irregular shelterwood treatment replicate was raw-planted in June 1995, as described for the group retention treatment. Seedlings were planted at a minimum spacing of 1 m from surrounding established trees, and at an average spacing of 2 m, depending on availability of microsites. The other half of each treat-

ment unit was left unplanted to provide long-term comparisons between naturally regenerated and planted areas.

5.3.3 **Single-tree selection** The intent of the single-tree selection (ST) treatment was to create or maintain a uniformly uneven-aged stand structure (Table 2; Figure 3). This is a traditional goal for a single-tree selection system (Smith 1986). Individual trees were marked-to-leave across all diameter classes to the 50% target removal level. The single-tree selection treatment units were not planted, and are being regenerated with only natural and advance regeneration.

6 SUB-PROJECT DESCRIPTIONS

The Lucille Mountain silvicultural systems trial was the first of several contemporary silvicultural systems projects to be established in the ESSF in British Columbia. It has provided many valuable data sets, some of them unique and most of them spanning 8 or more years to date. It has also functioned as the starting point in an adaptive management process that has continued with a variety of experimental and operational silvicultural systems blocks in the ESSF.

As a pilot project, the Lucille Mountain trial is unreplicated, and though the trial is valuable, its limitations are acknowledged. The lack of replication limits our ability to generalize the results to other sites; where possible, we have tried to mitigate this limitation by comparing our results to those of other silvicultural systems trials. The initial focus of the trial was the comparison of regeneration response and related influencing factors under a range of post-harvest stand structures. For this purpose, the clearcut was considered the "control" area; no equivalent unharvested control area was included. For the same reason, pre-treatment data collection was limited. For the purpose of other studies (e.g., light, arboreal lichens), uncut control areas were selected after project establishment from the adjacent uncut forest. Also, as a result of the topography of the site and the initial layout, the 0.2-ha patch cuts are lower in elevation than the other treatment units. Some design elements in the trial, such as the 1-ha size of each partial cut treatment unit and the narrowness of some treatment buffers, restrict the suitability of the site for certain types of research, such as wildlife habitat studies.

Section 6 describes the various sub-projects that have been undertaken at Lucille Mountain. Some of these sub-projects are complete, but most are ongoing, and the results should be considered interim relative to the long-term duration of these studies. Data from ongoing climate monitoring are described in detail because they provide fundamental background information for interpretation of many of the other studies at Lucille Mountain. These data are not published elsewhere. Results to date of other studies in this trial are presented in less extensive formats. Where portions of the data have been published elsewhere, or when publications are pending, these sources are indicated. Appendix 3 lists publications, theses, unpublished reports, and publications in progress that are based on studies at Lucille Mountain.

This Working Paper:

- presents and synthesizes some previously published data in a broader context, relating them to other studies at Lucille Mountain;
- augments earlier analyses with additional data, and examines response trends for longer than was previously possible; and
- presents various supplemental data and observations not published elsewhere to provide a broader base of published data for present and future interpretations of trial results.

Most of the studies were carried out in only some of the treatment units (Table 4), due to limitations of resources and to differing sub-project objectives. The treatment types, which are described in detail in Section 5, are abbreviated as follows in Table 4 and elsewhere:

CC	clearcut
PCS	summer-logged patch cut
PCW	winter-logged patch cut
GR	group retention
IS	irregular shelterwood
ST	single-tree selection
UN	unlogged

Locations of specific research installations are described and mapped in the Establishment Report (Jull et al. 1996). All research installations in the patch cuts were located in openings of 0.2 ha, not in the smaller openings along the edge of the treatment area (Section 5.2). Because there was no single designated unlogged control area, different portions of the unlogged stand adjacent to the cutblock were used in different sub-projects.

TABLE 4 *Treatment units in which various research topics were investigated at Lucille Mountain*

	Treatment unit						
Research topic	**CC**	**PCS**	**PCW**	**GR**	**IS**	**ST**	**UN**
Climate monitoring	✓	✓		✓			
Light measurements				✓	✓	✓	✓
Vegetation succession	✓	✓	✓	✓	✓	✓	
Natural regeneration	✓	✓				✓	
Planted regeneration	✓	✓			✓		
Response of residuals				✓	✓	✓	
Windthrow incidence				✓	✓	✓	
Arboreal lichen abundance					✓	✓	✓
Arboreal lichen growth rates				✓	✓		✓
Litter decomposition rates	✓	✓			✓		✓

6.1 Climate and Microclimate

BOB SAGAR, MIKE JULL, AND CRAIG DELONG

Key Results

- The Lucille Mountain research site shares many of the characteristics of the ESSF zone described in Section 3, such as a cold, moist, and snowy continental climate. A notable feature of the climate at this site is the relatively long frost-free period, often exceeding 100 days.
- Summer frosts were surprisingly uncommon, occurring on only 9 days during the 8 years at the long-term climate station located in the lower clearcut. Frost incidence appears to increase somewhat with elevation at this site. This relative lack of frost was attributed to effective cold air drainage off the sloping site. Due to the low incidence of summer frost, air temperature is not by itself considered to be a major deterrent to forest regeneration at this study site.
- Minimum nighttime 30-cm air temperatures were lowest in the open (unshaded) measurement locations of a given treatment.
- Throughout much of the growing season, mean daily soil temperatures were often below 10° C at the cooler, shaded microsites (throughout the group retention treatment, and on the shaded southern edge of the small patch cut treatment).
- Increasing elevation (approximately 110 m between the two climate stations) on the site results in a shorter growing season due to more frosts and increased duration of snow cover. The upper clearcut climate station had average daily minimum 1.5-m air temperatures that were 1.7° C lower and had 18% fewer growing degree-days than the lower clearcut site.
- Light levels in the partial cuts were substantially higher than in the pre-harvest forest, both above and below the shrub/herb canopy.
- Of the three partial cut treatments, average understorey light levels were highest in the irregular shelterwood and lowest in the single-tree selection treatments, but maximum light levels were highest in the group retention treatment.

6.1.1 Objectives

To begin to more confidently design appropriate silvicultural systems for high-elevation subalpine forests, a better understanding is required of the degree to which different harvest patterns and stand structures influence site and stand microclimate. Through their influence on microclimate, different residual stand structures may influence a variety of stand attributes, including establishment and growth of regeneration, growth of arboreal lichens, understorey vegetation, and snowmelt rates.

The objectives of the Lucille Mountain climate sub-project reported here are:

- to compare and contrast air, soil, and canopy microclimate between partial cut and clearcut site environments;
- to examine the light environment of the partial cut treatments and compare it to an unharvested stand; and
- to provide an ongoing long-term record of the subalpine ESSF climate at the Lucille Mountain site.

6.1.2 Background There have been very few climate data published for the ESSF zone in British Columbia. The data published as representative climate characteristics of the biogeoclimatic subzones of the ESSF (Pojar and Meidinger 1991; Reynolds 1997) are incomplete for many subzones, with few reporting stations and data of limited duration. The data that are available for the ESSFmm (Reynolds 1997) are based only on short-term measurements for two climate parameters (air temperature and precipitation) made at two geographic locations.

As discussed in Section 1, there are currently three long-term silvicultural systems studies in the interior of British Columbia that are monitoring climate in the ESSF and the effect of harvest practices on site microclimate. Of these, the Lucille Mountain Project is the longest running, with 8 years of monitoring to date.

Subalpine climates have long been characterized as harsh environments for forest management, tree establishment, and growth. Many factors, including low air temperature and soil temperature, high soil moisture, high vegetation competition (for light, soil moisture, and nutrients), snow cover duration, snowpress, and snowcreep, have been identified as potential environmental constraints to regeneration in the ESSF zone (Farnden 1994).

The temperature of both the air and soil are important environmental factors that affect the viability of subalpine sites for seedling growth. Summer frost has been identified as a serious problem at some high-elevation plantations (Stathers 1989; Steen et al. 1990; Black et al. 1991a, 1991b) and the physiological effects of frost on seedlings have been studied extensively (Delucia and Smith 1987; Lundmark and Hallgren 1987; Dang et al. 1992). It has been suggested that partial cutting of forests in frost-prone areas may enhance regeneration success by reducing frosts through the sheltering effects of the retained forest (Stathers 1989). Clearcut patch size (i.e., proximity to the uncut forest) greatly affects nighttime minimum air temperatures near the ground (Pettersen 1993; Groot and Carlson 1996). Frost damage is generally greatest near the centre of the larger openings in locations away from the ameliorating effects of stand edges (Jordan and Smith 1995; Groot and Carlson 1996).

Low soil temperature affects the growth and vigour of seedlings due to its effect on the roots' uptake of water and nutrients, which in turn affects the seedlings' ability to photosynthesize (Delucia 1986). In examining the effect of soils, vegetative cover, and topography on high-elevation clearcuts, Balisky and Burton (1995) found that depth of organic layer and percent vegetative cover had the largest effects on soil temperature. Soil temperatures in the clearcuts varied greatly according to microsite, and many of the seedling microsites were sub-optimal for seedling growth.

Light is a critical factor influencing tree growth (Pacala et al. 1994; Lieffers et al. 1999) and can be directly manipulated by forest management activities. Partial cutting can result in a wide range of light levels reaching planted tree seedlings (Coates and Burton 1999), and thus characterizing the light regime of partially cut stands is important for understanding the potential impact of the treatment on seedling growth.

6.1.3 Methods To monitor microclimate over a range of opening sizes, climate monitoring stations were set up in the clearcut, the 0.2-ha patch cut, and the group retention treatment units. Light measurements were taken in all three partial cut treatments and in the adjacent unharvested forest.

Instrumentation Three climate/microclimate monitoring stations (hereafter referred to as climate stations) were installed 24–26 June 1992, one on each of the large clearcut, a 0.2-ha patch cut, and a group retention opening. The basic climate variables measured at each climate station were air temperature and relative humidity, using Vaisala HMP35C sensors (Vaisala Inc., Woburn, Mass.), which combine a thermistor bead for air temperature and a capacitive relative humidity sensor. The Vaisala sensors were housed inside Stevenson screens at 1.5 m above the ground. Rainfall and solar radiation were measured at the clearcut climate station only. Rainfall was measured using a tipping bucket rain gauge (Sierra Misco Inc., Berkeley, Calif., Model RG2501) and solar radiation with a silicon cell pyranometer (Li-Cor Inc., Lincoln, Nebr., Model LI200S).

Microclimate measurements consisted of groups of air and soil temperature sensors (Campbell Scientific Canada Corp., Edmonton, Alta., Model 107BAM and 107 thermistors) placed at selected microsites within each silvicultural harvesting treatment. A group consisted of air temperature sensors at 5 and 30 cm above the ground surface and soil temperature sensors 10 cm beneath the ground surface. The thermistors were potted in epoxy inside 10-cm lengths of 0.95 cm (3/8 inch) aluminum tubing. The air temperature sensors were mounted between radiation shields consisting of two 15 × 15 cm plates of sheet aluminum and topped by a 30 × 30 cm plate, which was painted white on its upper surface.

In the clearcut, two temperature sensor groups were placed in open locations free from overtopping vegetative cover. In the group retention treatment, three sensor groups were placed in each of two microsite types, defined as "open" (in untreed areas between retained clumps of mature trees) and "clump" (under the canopy of clumps of mature retained trees). In the patch cut treatment, two sensor groups were placed in each of three microsites within the patch cut, including the centre of the patch cut, the north edge, and south edge. Sensor locations on north and south edges were located within 10 m of the closest stand edge. In general, the north edge sensor locations receive mid-day sun (albeit on a north-facing slope), while the south edge locations are shaded during the mid-day hours by the residual trees to the south.

No direct measurements of snow cover were made; however, we can infer the presence of snow cover greater than a given depth by examining the diurnal range in temperature measured by an aboveground temperature sensor. When a sensor is covered by snow, its diurnal temperature range decreases dramatically. Diurnal temperature ranges for uncovered sensors are rarely less than 5° C. A diurnal temperature range of less than 2° C was chosen as the threshold below which a sensor was said to be snow-covered. The cessation of snow cover in spring is well defined, as the diurnal temperature range typically jumps from >1 to 15° C in a few days. The onset of snow cover in the fall is more difficult to determine due to repeated episodes of snowfall and melting before deeper snow keeps the diurnal temperature range near 0° C until spring. Estimates of snow cover onset and cessation were made using unshielded thermistors mounted 5 cm above the ground.

In late May 1998, following completion of sixth-year measurements, climate stations were removed from the group retention and small patch cut treatments. To increase the elevational range of climate monitoring in the study area, a new climate station was installed in early June 1998 at approximately 1570 m in the upper portion of the clearcut treatment. The upper

clearcut climate station is located on a gently sloping bench, approximately 110 m higher than the lower clearcut climate station.

Instrumentation at the upper clearcut station consists of a Stevenson screen with a Vaisala temperature/relative humidity sensor (as described above) and three groups of sensors, each consisting of a 30-cm air temperature and a 10-cm soil temperature sensor. The air temperature measurements are made with 30 AWG chromel-constantan (Omega Engineering Inc., Laval, Que.) fine-wire thermocouples mounted on wooden stakes with no radiation shielding. The soil temperature sensors consist of twisted and soldered 24 AWG chromel-constantan thermocouples potted in epoxy contained in brass tubing. The soil temperature sensors were buried 10 cm beneath the organic-mineral soil interface. A 30-cm fine-wire thermocouple was also installed at the lower clearcut site to make comparisons with the top site valid.

Data collection All data were recorded using CR10 dataloggers (Campbell Scientific Canada Corp., Edmonton, Alta.). Because of the large number of sensors in the patch cut and group retention treatments, a multiplexer (Campbell Scientific, Model AM32) was used to interface some of the sensors with the dataloggers. The dataloggers took readings of all sensors once per minute. Hourly averages of solar irradiance (clearcut), relative humidity, and air temperature (Stevenson screens, all sites) were recorded. Daily totals of solar irradiance and rainfall were recorded at the clearcut site. Daily minimum, maximum, and mean values of air temperature, soil temperature, and relative humidity were recorded at all sites.

From 1992 until 1996 data were collected during the growing season only. Data collection began annually, after snowmelt in mid-June (except the first year post-harvest, when it began on 27 June), and continued until late September or early October. The dataloggers were removed from the site at the end of each season and reinstalled the next year. Starting in the autumn of 1996, year-round measurements were commenced in all locations.

Light measurements To facilitate efficient collection of light data, two trails were brushed out prior to harvest. One trail ran north/south along the boundary between the western and central rows of the partial cut replicates and the other east/west along the boundary between the northernmost and adjacent rows of the partial cut replicates. Using these trails, five randomly located sampling locations were sampled within four replicates of each of the three partial cut treatment units (Section 5.3). In addition, five locations were sampled at each of two sites in undisturbed mature forest adjacent to the partial cut harvest units.

On each sampling date, random locations were determined in the following manner: For each treatment unit replicate, a random number between 1 and 100 was chosen and used to determine the distance in metres to walk along the brushed trail before initiating measurements. Five random numbers between 1 and 20 were then selected and used to determine the number of metres along a transect at right angles to the brushed trail from the brushed trail to the sample location. To avoid effects of the brushed trail, the random number chosen for the first sampling location had to be greater than 1 or a new number was chosen.

At each sampling location, light transmission was measured using a hand-held integrating radiometer (Sunfleck Ceptometer, Model SF-80, Decagon Devices Inc., Pullman, Wash.). At each sample location, photosynthetic photon flux density (PPFD) measurements were taken at two canopy positions, one above all shrub and herb vegetation, to estimate overstorey canopy effects, and the other at 10 cm above ground level, to estimate combined overstorey and understorey effects. At each canopy position, an average was computed of four readings taken in the cardinal directions. Measurements were obtained on clear-sky days between 1100 and 1500 PST.

6.1.4 Results and discussion Table 5 and Figure 5 summarize selected growing-season climate characteristics for the clearcut site for the period 1992–1999. The mean growing-season temperature for the 8-year period was 11.4° C and the average rainfall was 199 mm. The measured total solar irradiance averaged 64% of the potential clear-sky value. The years with the highest solar irradiances (70% in 1994 and 68% in 1998) corresponded to the highest mean air temperatures.

Growing degree-days Seasonal totals of growing degree-days (GDDs), based on daily mean 1.5-m air temperatures >5° C, were typically near 500, with only 1994 and 1998 having significantly more (665 and 743, respectively).

On average, July and August appeared to have the most favourable conditions for seedling growth, averaging 223 and 218 GDDs, respectively. Interannual variation in monthly totals was great. (August totals, for example, ranged from 103 to 271.) There was also high intra-annual variability (e.g., 103 GDDs for all of August 1995 versus 130 in the first 15 days of September 1995). June may also have a significant number of potential GDDs, as the mean of 55 is based only on the last 11 days of the month; however, the presence of snow cover and subsequent cool post-snowmelt soil tempera-

TABLE 5 *Selected growing-season (20 June–15 September) climate parameters for the lower clearcut site from 1992 to 1999. Summer frosts (air temperature < 0° C) and date of first killing frost (air temperature < -3.9° C) were determined using the 30-cm shielded thermistors.*

Year	Mean air temp. 1.5 m (°C)	Total rainfall (mm)	Summer frosts (Jun 20–Aug 31)	Date of first killing frost[a] (T_a < -3.9° C)	GDD (mean air temp > 5° C)					% potential solar irradiation
					Jun	Jul	Aug	Sep	Total	
1992	10.6	9	6	22 Aug	43	245	213	5	506	64
1993	10.6	188	0	(7 Oct)	42	160	208	87	497	61
1994	12.6	170	0	3 Oct	80	274	252	59	665	70
1995	10.8	264	0	(25 Sep)	88	192	103	130	513	59
1996	11.2	208	0	23 Sep	48	225	226	46	545	62
1997	11.1	360	1	5 Oct	43	190	231	68	532	66[b]
1998	13.4	159	0	10 Oct	77	312	271	83	743	68
1999	10.6	230	2	(23 Sep)	22	189	239	44	494	65
Normal	11.4	199	1	25 Sep	55	223	218	65	562	64

[a] Dates in parentheses are last date of record for that year and indicate no killing frosts recorded as of that date.
[b] Data for period 23 July–15 September.

tures during the first half of the month may limit potential June GDDs. Mean monthly GDD trends are corroborated by field observations of conifer seedling phenology. Bud-break and new foliage growth typically began between 20 June and 1 July, and buds were set by 15 August.

Measured GDD accumulations between 1 and 15 September typically accounted for 10–20% of measured total growing-season totals. September GDD accumulations, combined with the relatively late average date of the first killing frost (25 September), suggest that September weather conditions in most years may allow trees at this ESSF site suitable conditions to photosynthesize and accumulate resources for current and future tree growth.

The annual totals of GDDs for 1997 and 1998 (the first 2 full years of year-round climate monitoring) were 787 and 1127, respectively. The 1998 total is slightly outside the range of 596–1029 reported by Reynolds (1997) for the ESSF zone. By contrast, annual GDD totals are reported to range from 751 to 1510 in the Sub-Boreal Spruce zone (SBS), from 978 to 2151 in the Interior Cedar–Hemlock (ICH), and from 240 to 427 for one reporting station in the Alpine Tundra (AT). The former two zones lie below the ESSF in elevation, while the latter is above it. The mean annual air temperatures for 1997 and 1998 were 2.0 and 3.2° C, respectively. Reynolds' reported range is -3.0 to +2.0° C. The fact that the GDD totals and mean annual temperatures for 1998 fall outside the reported range is indicative of the paucity of data available for the ESSF zone prior to this study.

Frost incidence The frost-free periods at the clearcut site for the years 1997–1999 were 117, 103, and 85 days, respectively (determined using the 1.5-m air temperatures for consistency with published data). Measurements for all 3 years indicate that the frost-free period at Lucille Mountain is in the upper range of, or exceeds the range of, 24–107 days reported for the ESSF zone by Pojar and Meidinger (1991). This, together with data on frost-free period for the years 1992–1996 (69, 93, 104, 98, and 93 days, respectively), although incomplete due to lack of data in May and early June, indicates that

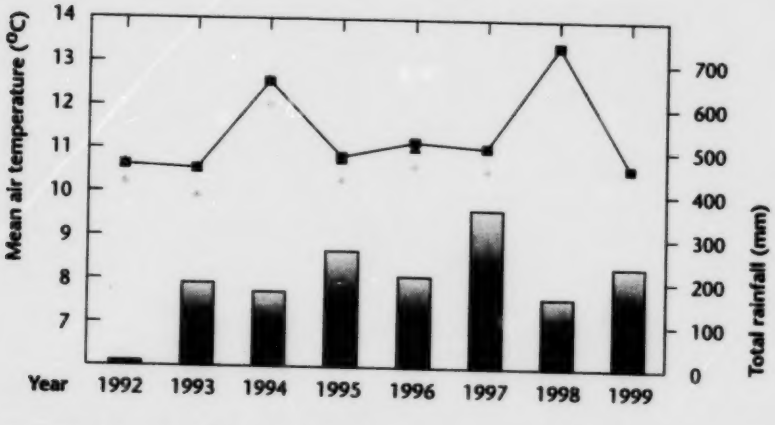

FIGURE 5 *Mean growing-season (20 June–15 September) air temperature at 1.5 m above the ground for the clearcut (■ connected by solid line), group rentention (▲), and patch cut sites (·). The bar graph shows total growing-season rainfall at the clearcut.*

frost-free periods of more than 100 days are probably not atypical for this site. The most likely explanation for the lack of summer frost observed in this study is that the consistent 25–45% slope of the research site provides good cold air drainage. This is typical of many mountainous areas in the ESSF zone with steep, sloping topography. In contrast, ESSF areas with plateau or lower slope, cold air–receiving locations would be expected to have a much greater incidence of frosts during the growing season. Another contributing factor to the lack of frost may be the frequent cloudy and wet conditions experienced at the site. Optimal conditions for radiative heat loss are clear skies, low humidity, and low wind speeds.

The average date of occurrence for the first killing frost (defined here as daily minimum 30-cm air temperatures of <-3.9° C as per Delucia and Smith 1987) was 25 September, but was as early as 22 August in 1992 and as late as 10 October in 1998. A total of nine summer frosts (defined here as daily minimum 30-cm air temperatures of 0.0° C or lower, occurring between 20 June and 31 August) were recorded, and occurred during only 3 of the 8 years of measurement. Only the frosts of 22 and 23 August 1992 (-4.1 and -5.0° C) were considered severe enough to be damaging to seedlings. While these frosts caused some visible damage, they occurred outside the period of maximum vulnerability (the period of stem elongation), from about 20 June to 15 August. Frosts of -2 to -3° C occurred on 15–16 July 1999 with little or no damage visible despite being in this period of vulnerability. The relatively few summer frosts recorded at Lucille Mountain during this study conflict with the conventional wisdom for sites in the ESSF zone, where frost has been considered a serious hindrance to plantation establishment (Stathers 1989; Steen et al. 1990; Black et al. 1991a, 1991b).

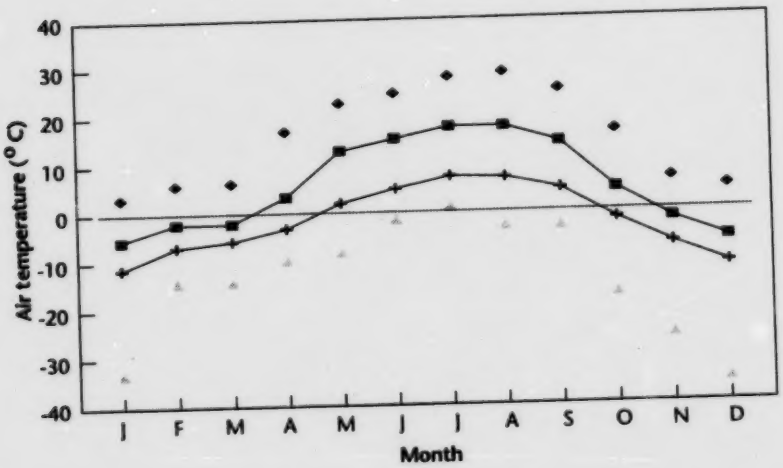

FIGURE 6 *Monthly means of daily minimum (+) and maximum (■) 1.5-m air temperature. Points not connected by lines are the extreme minimum (▲) and maximum (♦) temperatures for each month. Data for July, August, and September are from 1992–1999; data for the other months are from October 1996 through September 1999.*

Air temperature Figure 6 shows the monthly means of daily maximum and minimum 1.5-m air temperature, as well as the monthly extremes. Only the data for July, August, and September represent averages for the period 1992–1999; the remaining months are represented by data for only 3 years (October 1996 through September 1999). During summer, daily maximum air temperatures were typically 15–18° C and minimums were in the 5–8° C range. Extremes in daily temperature recorded at the site ranged from 28.6° C in August 1998 to -35.2° C in December 1996.

Figure 7 shows the daily minimum and maximum 1.5-m air temperatures for a complete annual cycle. Temperatures remained below freezing for most of the time during the 6 months starting in mid-October 1996 and ending in mid-April 1997. The season was punctuated by three periods of intense cold. It appears that snowfall may have completely buried the Stevenson screen for a brief period in late March, as indicated by the very small diurnal temperature variation. Temperatures increased rapidly after mid-April, with the last sub-freezing minimum temperature occurring in late May. The mean annual temperature for the 1-year period shown in Figure 7 was 0.8° C. The mean annual temperatures for the calendar years 1997 and 1998 were 2.0 and 3.2° C, respectively.

Snow cover duration Table 6 gives dates of snow cover cessation for the clearcut, small patch cut, and group retention climate monitoring sites. Snow cover is spatially variable, and the observations reported here are based on from one to three measurement locations per microsite. These observations are presented as a sample to give the reader a general idea of snow cover duration at the site and should not be assumed to be representative of all locations within the given treatment units. Many of the larger seedlings probably emerged from the snowpack as much as 7–10 days prior to the reported dates of snow cover cessation due to their height and enhanced melting around them.

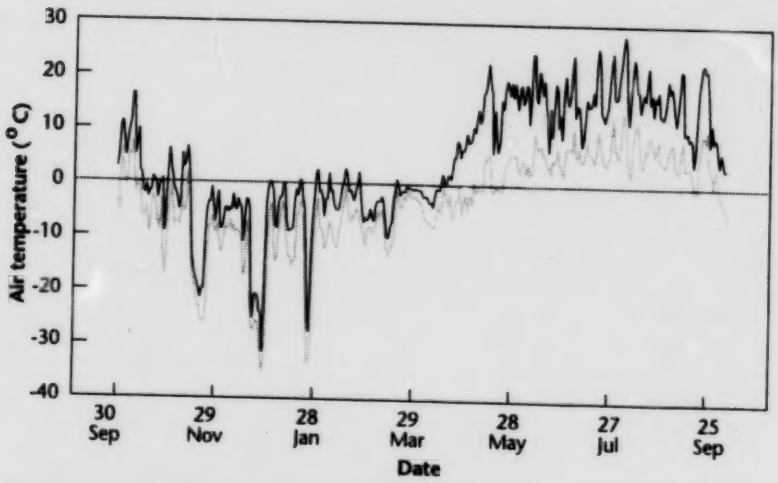

FIGURE 7 *Annual cycle of daily minimum ( ) and maximum ( ) 1.5-m air temperatures beginning on 30 September 1996.*

TABLE 6 *Approximate cessation dates of snow cover at the clearcut, patch cut, and group retention climate station sites, 1997–1999*

	Clearcut	Patch cut			Group retention	
Year	Open	South	Centre	North	Clump	Open
1997	24 May	23 May	20 May	17 May	-	-
1998	4 May	30 April	1 May	1 May	27 April	7 May
1999	3 June	-	-	-	-	-

The cessation of snow cover came as early as 4 May in 1998 and as late as 3 June in 1999 at the clearcut site. At the patch cut, cessation of snow cover was from 1 to 7 days earlier than at the clearcut, depending on the microsite and year. The pattern of snowmelt for the small patch cut in 1997 was as might be expected; with the north edge (south-facing) microsite melting first and the south edge (north-facing) microsite melting last (6 days later). In 1998 all three microsites at the small patch cut finished melting within a day of each other. The 1 year for which data were available at the group retention site (1998) shows an interesting pattern. Snow cover cessation for the clump microsite was the earliest of all microsites (27 April), while that at the open microsite was the latest (7 May). This is similar to the pattern observed in natural subalpine parklands. The canopies of clumps intercept snowfall, which is subsequently melted, sublimated, or redistributed by the wind to the surrounding open areas. Clumps also absorb shortwave irradiance and reradiate it, causing more rapid snowmelt around them.

Onset of snow cover typically occurred in late September or early October in all treatment units, giving a snow-free season ranging from approximately 120 to 150 days. Deep snow that caused the diurnal temperature variation to settle near 0° C for the winter generally occurred in late October.

Effects of elevation Elevational differences undoubtedly occurred between treatment units in this study, but are difficult to quantify due to the confounding effects of the treatments. For this reason we have chosen to compare two clearcut sites at different elevations. Table 7 compares air temperatures and GDDs recorded at the lower clearcut climate station (1570 m) with those

TABLE 7 *Comparison of 1.5-m Stevenson screen air temperatures and 30-cm air temperatures at upper and lower clearcut sites for 1998 and 1999 growing seasons (20 June–15 September)*

Year	Site	Mean daily max 1.5 m T_a (°C)	Mean daily min 1.5 m T_a (°C)	Mean daily min 30 cm T_a (°C)	Number of frosts[a]	Number of GDDs
1998	upper	17.8	6.5	4.4	1	631
	lower	19.0	8.2	6.0	0	743
1999	upper	14.8	4.0	2.4	8	391
	lower	16.0	5.7	3.4	4	494

Notes: *Lower site means based on one replicate for 1.5 m T_a and 30 cm T_a.*
Upper site means based on one replicate for 1.5 m T_a and three replicates for 30 cm T_a.

[a] *Summer frosts based on minimum 30-cm air temperatures 0° C or below as measured by unshielded fine-wire thermocouples.*

from the upper clearcut climate station (1460 m) for the 1998 and 1999 growing seasons. Minimum 1.5-m air temperatures averaged 1.7 ° C less at the upper site during both the 1998 and 1999 growing seasons. Maximum 1.5-m air temperatures averaged 1.2° C lower at the upper site during both seasons. During the two growing seasons examined, there were a total of nine growing-season frosts at the top site and four at the lower site. During the first site visit of 1999 (15 June) only a few shallow patches of snow cover remained near the lower climate station, while nearly continuous snow cover of 20–30 cm was observed at the upper climate station.

The expected temperature difference due to the 110-m elevation change is between 0.5 and 1.0° C (Wallace and Hobbs 1977). Part of the temperature difference between the upper and lower sites may result from the gentle slope of the upper site slowing down cold air drainage. The upper site had 17% fewer GDDs over the course of two growing seasons. The differences between these two sites illustrate how a relatively small change in elevation and/or topography can lead to a substantial difference in the number of growing-season frosts, snow cover duration, and GDDs.

Comparison of microclimate of the silvicultural treatments Figure 8 and Table 8 summarize daily minimum 30-cm air temperatures and daily mean 10-cm soil temperatures at the various microsites for the 1992–1997 growing seasons. Maximum temperatures for the 30-cm shielded thermistors are not discussed here because the thermistors were found to read as much as 2–4° C too high, under conditions of bright sunshine on the shields, when compared with an aspirated psychrometer.

Nighttime minimum air temperatures were always lower at locations within openings that were away from the influence of adjacent forest cover. The mean minimum temperature averaged 4.1° C at the open locations of the group retention site compared with 5.0° C within tree clumps. In the patch cut treatment, the mean minimum temperature averaged 4.5° C at the centre locations compared with 5.0° C at south edge and 4.7° C at the north edge. The observed 0.3° C difference between the north and south edge locations in the patch cut may be attributed to cold air drainage downhill from the cooler centre of the patch cut, and cold air damming by the uncut stand edge. Paradoxically, among sensors located in openings, the 32-ha clearcut had the highest average minimum nighttime temperature at 4.9° C, compared to 4.5° C in the patch cut and 4.1° C in the group retention treatment. One possible explanation for this phenomenon may be that the extensive open area of the clearcut encourages higher wind speeds (therefore, turbulent mixing) and more effective cold air drainage, whereas the sheltered partial cut treatments may inhibit wind and cold air drainage.

Low air temperature has been found to cause irreversible reductions in photosynthesis in Engelmann spruce when temperatures drop to -4° C (Delucia and Smith, 1987). Frost events of this severity during the growing season (20 June–31 August) were recorded only on two nights (22 and 23 August 1992) in the 8 years of this study. This suggests that in general, damaging low air temperatures during the growing season do not appear to be an important factor limiting regeneration at this study site. These observations do not, however, discount the possibility of infrequent severe frosts during the growing season at this site during some years.

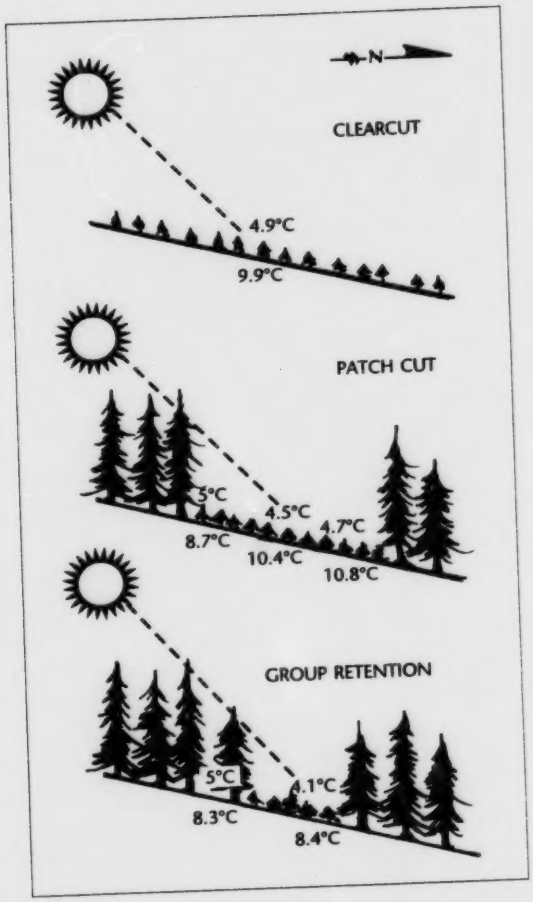

FIGURE 8 *Mean growing-season 10-cm soil temperatures and daily average minimum 30-cm air temperatures (°C) at the different microsites within the clearcut, patch cut, and group retention sites, 1992–1997.*

TABLE 8 *Seasonal mean minimum 30-cm air temperatures (Air) and seasonal mean 10-cm soil temperatures (Soil) at the clearcut, patch cut, and group retention sites, 1992–1996*

	Clearcut		Patch cut						Group retention			
	Open		North edge		Centre		South edge		Open		Clump	
Year	Air (°C)	Soil (°C)	Air (°C)	Soil (°C)	Air (°C)	Soil (°C)	Air (°C)	Soil (°C)	Air (°C)	Soil (°C)	Air (°C)	Soil (°C)
1992	4.0	9.9	4.3	10.7	4.1	9.9	5.5	8.7	3.4	8.2	4.0	8.2
1993	5.1	9.9	4.6	11.0	4.4	10.8	4.5	8.7	3.9	8.3	4.3	7.9
1994	6.4	10.6	6.1	12.1	5.6	11.2	5.9	9.3	4.9	9.0	6.1	9.0
1995	4.9	9.7	4.7	11.1	4.7	10.6	5.0	8.8	4.1	8.4	5.9	8.3
1996	4.6	9.7	4.2	10.0	4.1	9.7	4.8	8.4	4.4	8.1	4.9	7.9
1997	4.4	9.6	4.0	10.3	4.3	9.8	4.6	8.6	4.1[a]	8.4[a]	4.9[a]	8.8[a]
Mean	4.9	9.9	4.7	10.8	4.5	10.4	5.0	8.7	4.1	8.4	5.0	8.3

[a] *Includes data from 23 July to 7 October only.*

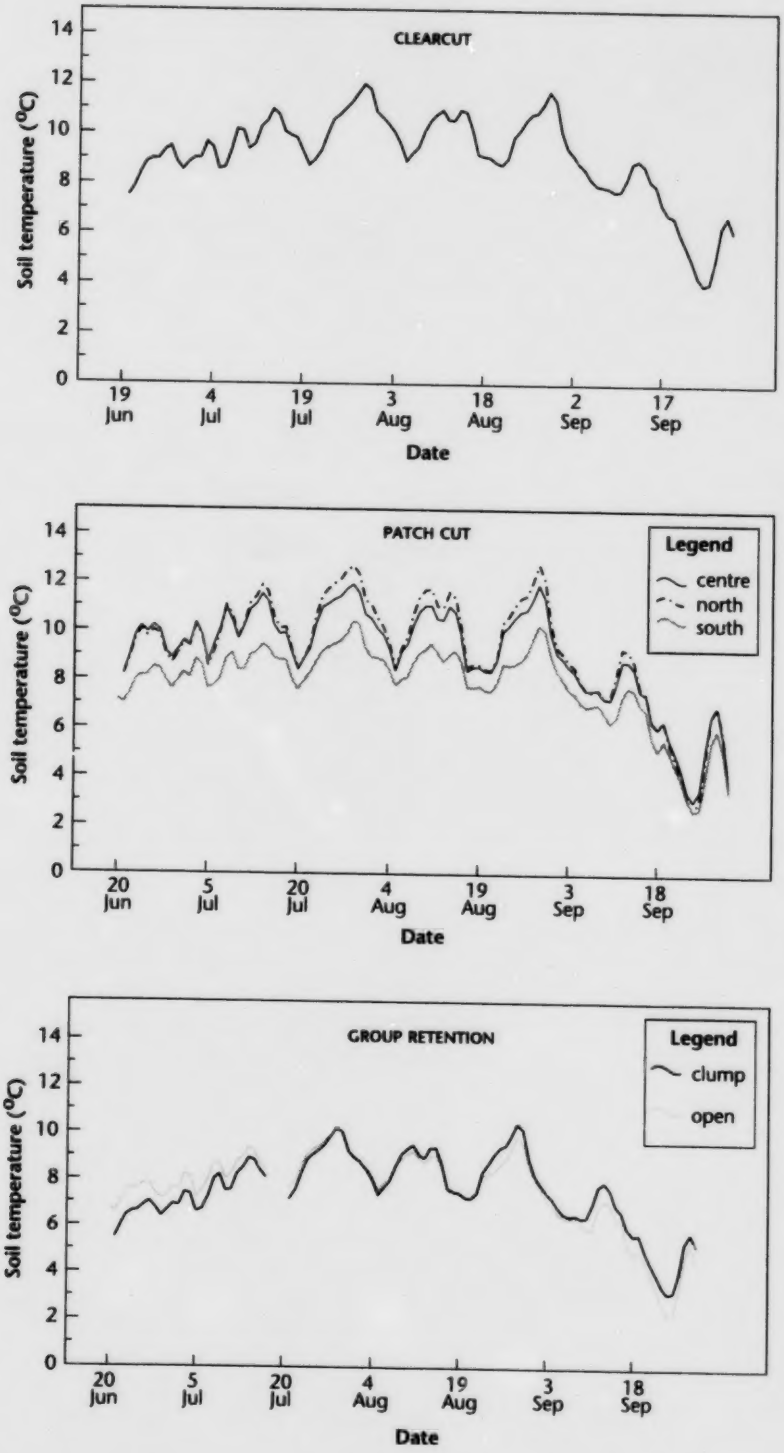

FIGURE 9 *Daily mean 10-cm soil temperature during the 1996 growing season for the clearcut, patch cut, and group retention sites and their various microsite treatments.*

Effects on soil temperatures The effect of the shelter of forest edges on mean soil temperature was most apparent in the case of the patch cut treatment, where the soil temperature averaged 2.1° C cooler at the shady south edge locations than at those on the sunnier north edge. Among the sites, soil temperature was lowest in the group retention treatment, a fact that again can probably be attributed to greater solar loading on the clearcut and patch cuts, with the exception of the south edge locations in the patch cuts. In these discussions, we are making the tacit assumption that the soil and the shrub/herb layers are homogeneous at all the sensor locations. It is possible that undocumented differences in soils and vegetation might explain some of the differences between treatments.

Figure 9 shows the daily mean 10-cm soil temperature at the three sites and for the various treatments during the 1996 growing season. Soil temperatures at both sheltered and open sensor locations in the group retention site and those at the shaded south edge location of the small patch cut stayed consistently below 10° C during the growing season, and periodically dipped below 8° C. Soil temperatures in all treatments dropped below 8° C in early September.

Delucia (1986) showed that photosynthesis in Engelmann spruce begins to decline at soil temperatures below 10° C. Because that study was performed in a greenhouse with high ambient air temperatures, caution should be used in considering 10° C as a threshold for declining photosynthesis in the field environment. However, Delucia's work does illustrate the limiting effect of soil temperature on photosynthesis. The observed low soil temperatures at Lucille Mountain may be an important limiting factor to tree growth in cooler microsites throughout the growing season and at all microsites early and late in the growing season. Also, while shading by residual trees in some treatments probably contributed to lower soil temperatures, other possible causal factors need to be considered, such as the effects of logging practices on the depth of the organic layer and herb/shrub cover. Longer monitoring of seedling regeneration performance in different treatments and microsites will determine the practical significance of soil temperature differences on seedling growth in the ESSF.

Light regime of partially cut stands All partial cutting treatments substantially increased light levels both above and below the shrub/herb canopy, compared to those in the uncut forest (Figure 10). Light levels in the uncut forest, as measured by PPFD, were only 4% (below the shrub layer) and 17% (above the shrub layer) of background light levels (1400–1600 µmol/m^2/s). Light levels were most increased in the irregular shelterwood, where they were 25% of background levels below the shrub layer and 61% above the shrub layer. In the single-tree selection treatment, they increased only to 19% of background levels below, and 43% above, the shrub layer. The single-tree selection treatment likely had the lowest light levels because more stand structure was left in the sapling to pole size classes, increasing the amount of shading by the tree canopy (Section 5.3.3).

The mean PPFD of 55 µmol/m^2/s beneath the shrub canopy for the uncut forest is just above reported levels of the light compensation point for white spruce and subalpine fir growing in understorey environments (34 and 36 µmol/m^2/s respectively; Carter and Smith 1988). The means for the partially cut stands (257–332 µmol/m^2/s) are above the reported level of light saturation for natural white spruce and subalpine fir growing in understorey environments

(149 and 163 µmol/m²/s, respectively) (Carter and Smith 1988). However, they are below light levels indicated by Coates and Burton (1999) for optimal performance of spruce and subalpine fir. The light levels recorded above the shrub/herb layer in the partial cuts are near optimal for subalpine fir (Coates and Burton 1999). In the absence of cutting, seedling establishment beneath the shrub/herb layer would be difficult, given the light regime represented by the uncut stand. Light conditions in the partial cuts appear to be adequate for seedling establishment, although they may not be optimal, especially for spruce (Section 6.4). Overall, the best partial cut treatment for improving average light conditions for seedlings appeared to be the irregular shelterwood, but the variability and maximum light levels were higher for the group retention due to the variable openness created by this treatment (Section 5.3).

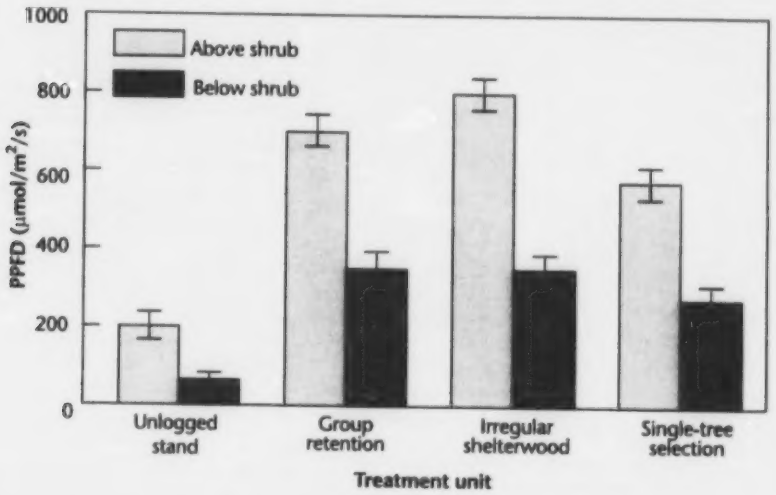

FIGURE 10 *Photosynthetic photon flux density (PPFD) measured above and below the shrub/herb layer for three different partial cut treatments (irregular shelterwood, group retention, and single-tree selection) in the unlogged stand. Error bars are ± 1 SE of the mean.*

6.2 Vegetation Succession

CRAIG DELONG

Key Results

- Treatments that exposed mineral soil (e.g., clearcut, summer patch cut) resulted in the greatest change in vegetation.
- There was little vegetation recovery on most affected sites 2 years after harvest.
- Recovery of shrub and herbs towards the pre-disturbance condition appeared to occur within 8 years of harvest regardless of treatment.
- Declines in most mosses occurred regardless of treatment, likely in response to drying induced by increased incident solar radiation at the moss interface.

6.2.1 Objective The objective is to determine the change in plant presence and abundance over time in response to all six silviculture treatment regimes (clearcut, summer patch cut, winter patch cut, group retention, irregular shelterwood, and single-tree selection).

6.2.2 Methods Four arrays of three 5 × 5 m plots were established prior to harvest in each of the six treatments. For each plot, percent cover of all plant species was recorded. In addition, for all species within the shrub layer (woody material <10 m in height), the average height of each species was recorded. Pre-harvest data were collected in 1990. Plots were reassessed 2 (1993), 4 (1995), and 8 (1999) years post-harvest.

6.2.3 Results

Pre-treatment Due to relatively homogeneous site conditions pre-treatment, vegetation was quite similar for all sub-plots, except for six of the winter patch cut sub-plots, which had lower shrub cover, higher cover of the herb *Cornus canadensis*, and higher cover of the mosses *Ptilium crista-castrensis* and *Hylocomium splendens*.

Two years post-treatment (1993) Where harvesting was completed on a firm snowpack (i.e., irregular shelterwood, group retention, single-tree selection, and winter patch cut), there was little change to the vegetation except for a large decrease in tree cover due to harvesting and an overall reduction in plant cover. The only species change for these units was the addition of small amounts (i.e., <1% cover) of *Epilobium angustifolium* and *E. ciliatum* in a few of the plots.

Where harvesting was completed in summer or with a shallow snowpack (i.e., clearcut and summer patch cut), there were significant changes to the vegetation, especially where the humus layer had been removed and mineral soil exposed. For example, one clearcut plot went from 14 to three species, and from shrub, herb, and moss covers of 75, 15, and 90%, respectively, to 0.1, 0.1, and 0%. For the clearcut treatment as a whole, there was an average loss of four species per plot. For the summer patch cut treatment, the average loss was 2.75 species per plot. The most common species to be lost were the herb *Cornus canadensis* and the moss *Brachythecium hylotapetum*. New species that tended to establish on the freshly exposed mineral soil were the shrub

Ribes laxiflorum, sedges (*Carex* spp.), the grass *Vahlodea atropurpurea*, and mosses from the genus *Polytrichum*.

Four years post-treatment (1995) Regardless of treatment, the cover of the shrub and herb layers was either stable or increased since the previous measurement. In some cases, the herb cover recovered to near or above pre-disturbance levels (Figure 11). The cover of the moss layer continued to decrease irrespective of treatment (Figure 12).

Recovery of the vegetation was most evident in the clearcut, where the plot that had only three species in 1993 had 12 species by 1995. The rush *Luzula*

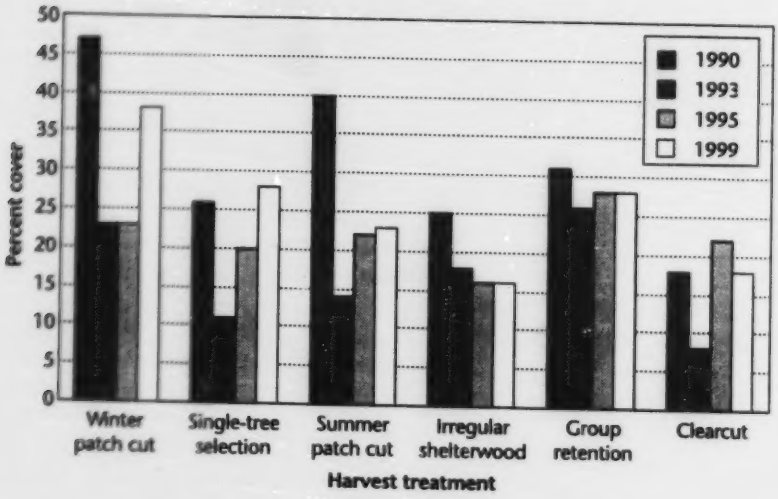

FIGURE 11 *Percent cover of the herb layer over time in response to different harvest treatments (pre-harvest = 1990).*

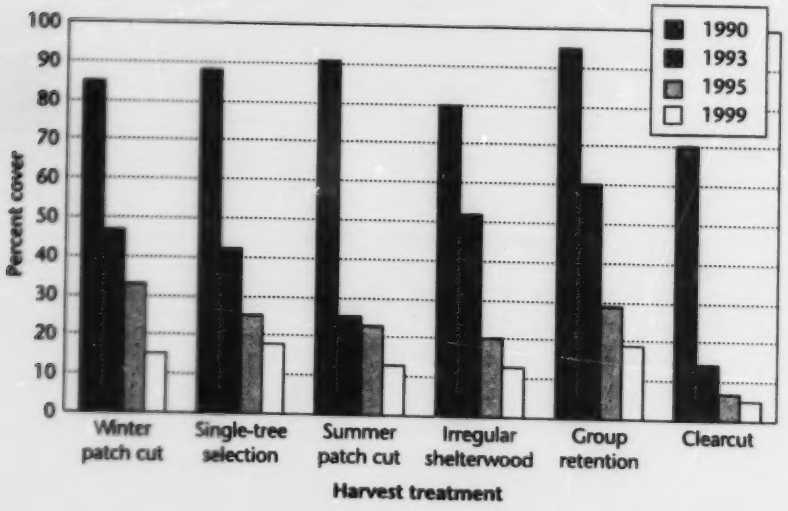

FIGURE 12 *Percent cover of the moss layer over time in response to different harvest treatments (pre-harvest = 1990).*

parviflora, which established on plots where mineral soil had been exposed, was the only new species to become established since 1993.

Eight years post-treatment (1999) Number of species and cover generally stabilized or increased since the previous measurement period, with the exception of the moss layer cover, which continued to drop regardless of treatment (Figure 12).

6.2.4 Discussion The most significant changes in vegetation were in response to removal of the humus layer and exposure of mineral soil. This makes intuitive sense, since all the plant material of mosses and many herbs are totally contained within the organic layer. The exposure of mineral soil has allowed some species to establish that were not present prior to harvest.

The decrease in moss cover irrespective of treatment is likely due to increased solar radiation causing drying of the humus layer. This effect may last until tree crown area has built up enough to reduce the solar energy input to the humus layers to pre-disturbance levels.

6.3 Natural Regeneration

ANDREA EASTHAM

Key Results

- Cone crop periodicity is independent of harvesting system.
- Seed availability limits regeneration in clearcut treatments.
- Exposed mineral soil increases number of germinants in patch cut and single-tree selection treatments.
- Mortality of seedlings, combined with low levels of ingress, result in fewer seedlings per hectare each year.
- Spruce and subalpine fir seedlings growing in the single-tree selection treatment are shorter and have smaller crowns compared to those in the clearcut or patch cut treatments.

6.3.1 Objective The objective is to determine the biological limits for viable subalpine fir and Engelmann spruce seed production and dispersal among partial cut and clearcut harvest treatments, and to determine germination and seedling growth within harvest and seedbed treatments.

6.3.2 Methods Five 40-m^2 natural regeneration plots were established post-harvest in the clearcut (CC) and single-tree selection (ST) treatments, and four plots in the patch cut (PCS). A plot consisted of eight seed traps and nine 2-m^2 germination plots; a germination plot consisted of four seedbed treatments: 1) disturbed and seeded (DS), 2) disturbed and not seeded (DN), 3) undisturbed and seeded (US), and 4) undisturbed and not seeded (UN). One plot in the selection harvest treatment, and two plots in the patch cut treatment, had fewer than nine germination plots in the 40-m^2 plot due to space limitations. Cone crop ratings, cone and seed dissections, seed evaluations, and germinant counts were conducted from 1993 to 1996. Seedling height and crown dimension measurements commenced in 1998, along with assessment of seedbed cover.

6.3.3 Results Natural regeneration results up to 1996 have been reported; see Eastham and Jull (1999) for details on cone crop periodicity, seed dispersal, seed quality, and germination. Only one heavy cone crop has occurred since the trial was established and that was in 1993. The number of sound seed from collected cones has been low in light cone crop years. The frequency of cone crops appears to be independent of harvest treatment. The species composition of the post-harvest stand was reflected in the amount of seed collected per species. At Lucille Mountain, there are more cone-bearing subalpine fir than spruce trees in the post-harvest stands, and more seeds per cone for subalpine fir, with the result that more subalpine fir than spruce seed has been collected in the seed traps among all harvest treatments. The number of subalpine fir and spruce germinants in 1994 in the partial harvest treatments (Figures 13 and 14) reflects only 0.5 and 5.7%, respectively, of the seed collected per hectare in traps. Few or no seeds of either species have been collected in the clearcut treatment. Direct seeding increased the number of subalpine fir and spruce germinants in the clearcut treatment regardless of whether the seedbed had been screefed during seedbed preparation. The undisturbed plots in the clearcut were more disturbed during harvest than the undisturbed plots in the two other harvest treatments. Seedbed disturbance to expose mineral soil increased germination of both species in the patch cut and single-tree selection harvest treatments.

The number of subalpine fir and spruce seedlings of the original cohort, established 1994–1997, has steadily declined in all silvicultural systems over the first four growing seasons (Figures 13 and 14). The single-tree selection treatment continues to have the highest subalpine fir seedling density, by seedbed treatment and in total. Direct seeding with subalpine fir had no effect because there was an abundance of seed produced naturally in the single-tree selection stands. The patch cut has the most spruce seedlings per hectare in the DS treatment, but the single-tree selection has the most spruce overall again, suggesting a greater source of seed from the remaining stand structure with this silvicultural system.

Both subalpine fir and spruce seedlings were shorter and had smaller crowns (volume) in the single-tree selection treatment (Figure 15). Combined across all silvicultural system treatments, subalpine fir and spruce seedlings growing in the DS seedbed treatment were taller and had greater crown volume compared to seedlings from the other seedbed treatments.

All of the silvicultural systems have some seedbeds with exposed rock and or mineral soil 5 years after the last disturbance. In the clearcut, 68 of the 178 plots assessed (38%) have exposed rock and 29% have exposed mineral soil. The patch cut and single-tree selection systems have exposed rock in approximately 30% of the plots, but only exposed mineral soil in 3 and 10% of the plots, respectively. Nurse logs, needle litter, and living roots as part of the seedbed surface condition were found only in the single-tree selection system. Coarse and fine woody debris, in all stages of decomposition, was present in all silvicultural systems but was more frequent in the single-tree selection treatment.

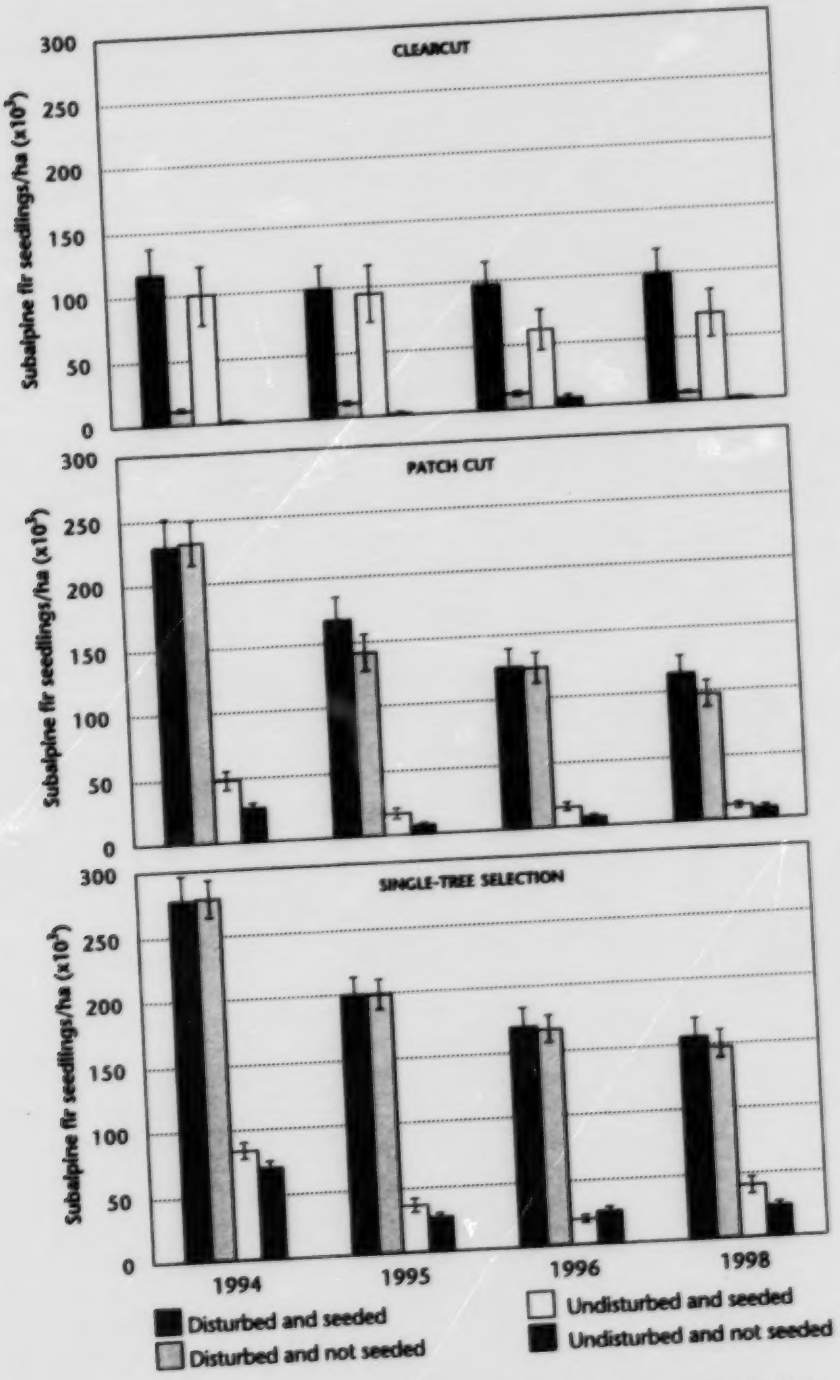

FIGURE 13 *Annual mean number of subalpine fir seedlings per hectare in three harvest treatments (clearcut, patch cut, and single-tree selection) and four seedbed treatments. Error bars represent treatment means (± 1 SE). n=5 in the clearcut and single-tree selection treatments, and n=4 in the patch cut.*

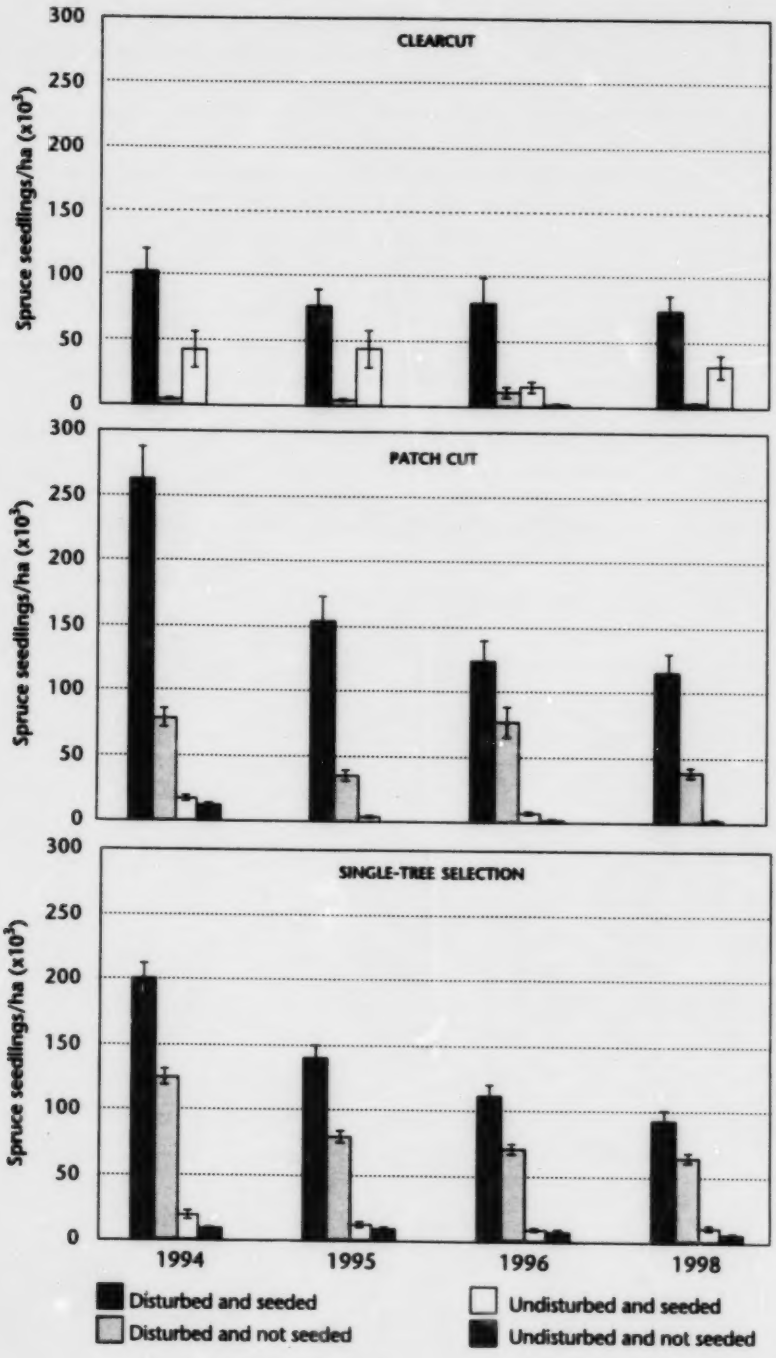

FIGURE 14 *Annual mean number of spruce seedlings per hectare in three harvest treatments (clearcut, patch cut, and single-tree selection) and four seedbed treatments. Error bars represent treatment means (± 1 SE). n=5 in the clearcut and single-tree selection treatments, and n=4 in the patch cut.*

6.3.4 Discussion An ample natural seed supply, combined with seedbed preparation, favoured germination and conifer seedling survival in the single-tree selection treatment, but germinant growth has been negatively affected. These results are similar to those from comparable studies in British Columbia. Feller (1997) found fewer subalpine fir and spruce seedlings on undisturbed seedbeds in the southern interior of British Columbia compared with mineral soil or burned seedbeds. In the Cariboo Forest Region, added seed had no effect on seedling densities where seed supply was not limiting, but scarified seedbeds had greater numbers of both subalpine fir and spruce seedlings 5 years after logging (Newsome et al. 2000). However, 7 years after logging, the heights of both subalpine fir and spruce naturally regenerated seedlings were not sufficient to meet the height requirement in the existing stocking standards being applied to that area. It remains to be seen whether the "lots of small seedlings" establishment strategy used in the single-tree selection system, or the "fewer but bigger seedlings" establishment strategy used in the patch cut and clearcut, is the preferred situation at this stage in the development of the stand.

Predicting seed supply to maximize natural regeneration in the pre-harvest planning stages is not a new idea (Alexander and Edminster 1983; McDonald and Abbott 1994), and Greene and Johnson (1994) have gone so far as to develop a predictive model based on tree and seed data for 15 species that estimates the expected number of seeds produced by a stand. If the amount and rate of natural regeneration at high elevations is not compatible with the management objectives for a site, direct seeding and planting could

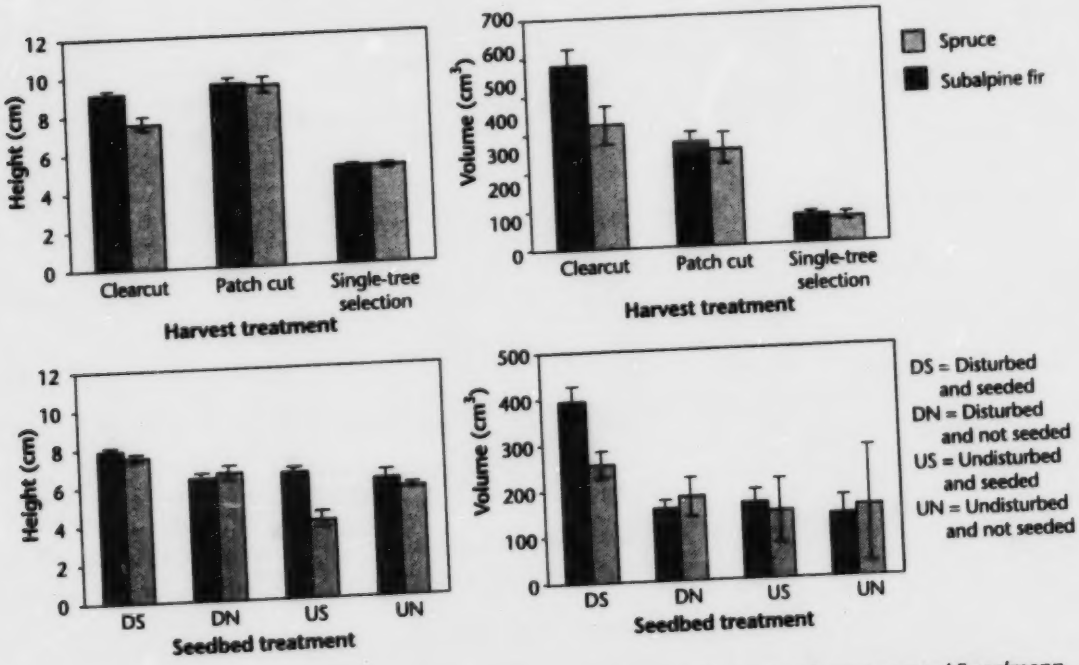

FIGURE 15 *Mean (±1 SE) seedling height (cm) and crown volume (cm³) of naturally regenerated Engelmann spruce and subalpine fir seedlings by harvest treatment and seedbed treatment. All seedlings in the original cohort were measured and used to calculate population means.*

be used to increase density (McCaughey et al. 1991) and adjust for species composition in the future stand.

Foresters could increase opportunities for natural regeneration in the ESSF zone by using harvest systems that enhance conifer seed availability and distribution through well-planned distribution of upwind seed sources, and by applying seedbed treatments prior to an anticipated moderate to heavy seedfall. (See also Section 7.2 for further discussion.)

6.4 Planted Regeneration

CLEO LAJZEROWICZ, MIKE JULL, CRAIG DELONG, AND MIKE WALTERS

Key Results

- Overstorey shelter appeared to protect Engelmann spruce seedlings from visible summer frost damage. Incidence of first-year apparent frost damage to buds and foliage was 6% in the irregular shelterwood, 24% in the 0.2-ha patch cuts, and 48% in the 32-ha clearcut. For spruce, treatment effect on frost incidence was significant ($p<0.01$). However, there was no clear effect on subalpine fir; as well, observations of apparent frost damage to subalpine fir foliage (if any) were confounded by foliage damage from other possible pathogenic causes.
- In the clearcut treatment where August 1992 frost damage was most severe, spruce seedlings frost-damaged after planting had significantly higher ($p<0.01$) cumulative mortality rates to 1998 (28%) relative to undamaged seedlings (8.6%).
- Across a range of treatments from the clearcut to the shelterwood, understorey light availability decreased by an average of 50% and mean growing-season soil temperature decreased by 2° C.
- Height, diameter, and current year leader growth of both Engelmann spruce and subalpine fir seedlings decreased with increasing canopy retention (clearcut > patch cut > shelterwood). Environmental factors significantly influencing this overall treatment effect included understorey light availability, soil temperature, and vegetation competition indices.
- Results to date suggest that subalpine fir is able to tolerate lower light levels and is less sensitive to low soil temperatures than Engelmann spruce. Initial post-harvest vegetation competition levels were lowest in the clearcut due to the impact of summer harvesting on competing vegetation. However, the treatments that substantially increased light availability (clearcut and summer patch cut) resulted in the greatest increase over time in vegetation competition indices.
- Proximity of residual leave-trees had local negative effects on above- and belowground growth of seedlings: location of planted seedlings less than 5 m from leave-tree boles resulted in growth suppression relative to other planting locations.
- Nitrogen availability does not appear to be limiting to seedling growth. N fertilization had no effect on height and diameter increment, and foliar N status was adequate for growth of both species.

This section includes results from three separate studies examining the response and factors influencing the response of planted seedlings of Engelmann spruce and subalpine fir to the three silvicultural systems (32-ha clearcut, 0.2-ha patch cuts, and irregular shelterwood).

6.4.1 Objectives The objectives are:

- to compare responses of planted subalpine fir and Engelmann spruce seedings to three different silvicultural treatments (irregular shelterwood, summer patch cut, and clearcut) spanning a range of residual stand retention patterns;
- to compare and quantify the effects of silvicultural treatments on a number of potential ecological factors affecting conifer seedling growth, including soil temperature, light, and nitrogen (N) availability;
- to quantify the effects of differences in light, N availability, and soil temperature on seedling growth; and
- to compare changes over time in vegetation competition for light in the three silvicultural treatments.

6.4.2 Methods

Establishment of planted seedlings In the clearcut, summer patch cut, and irregular shelterwood treatments, a total of 4200 subalpine fir and 4200 Engelmann spruce were summer-planted in 1992 in fourteen 40 × 40 m plots (five in the clearcut, four in the patch cut, and five in the irregular shelterwood). Stock types planted were 2-year-old Engelmann spruce "plug" stock grown in polystyrene blocks in a greenhouse (2+0 PSB415S) and subalpine fir that were similarly greenhouse-grown for 2 years and then out-planted for 1 year (2+1 PSB415S). In each of these field installations, three alternating rows of each species (45 trees per species per installation) were designated as permanent sample rows, two alternating rows as ecophysiology rows (named "destructive-sample" and "buffer" rows in the working plan), and one alternating row as a vegetation competition assessment row. The layout of the rows is shown in the Establishment Report (Jull et al. 1996). Where necessary, trees were individually numbered for reference.

Permanent sample trees Symptoms of apparent frost damage, including browned foliage and dead leaders, were observed on some seedlings in early September 1992. These symptoms were corroborated by measurements of severe frosts at adjacent climate stations in mid-August 1992. Systematic assessments of first-year damage to seedlings in permanent sample rows were conducted in the summer of 1993. Trees were rated and coded for apparent frost damage, including seedling mortality, dead terminal leaders, dead (unflushed) terminal buds, and dead or browned-off lateral foliage.

Starting in September 1993 (Year 2 post-harvest), seedlings in permanent sample rows were measured annually up to 1996 (Year 5), and again in 1998 (Year 7). Each measurement year, seedlings were measured in the late summer or early fall following setting of the terminal bud. Data collected at each measurement for each tree included:

- total height from base to tip of the terminal leader;
- current year's leader growth;

- an assessment of seedling vigour (good, medium, poor, dead); and
- general comments about seedling health and form.

In analyses of observations of first-year apparent frost damage, observations from all assessed permanent sample rows were included. To provide an adequate sample size for these analyses, data were pooled by treatment and species for all plots. Approximately 600 spruce and 600 subalpine fir were examined.

To analyze silviculture treatment effects on size and growth of potential "crop trees" in the research plots, the seedling sub-population representing the largest 700 sph of each species was post-stratified from the entire study population after the 7-year remeasurement. Based on a 1250 sph planting density for each species, these trees, termed "the top 700 sph," represented the tallest 55% of the planted stock in 1998. The decision to analyze the top 700 sph at Year 7 was made for two reasons: 1) 700 sph is the current minimum stocking standard for mesic sites in the ESSF; and 2) at Year 7, the tallest 700 sph are probably the portion of the population most responsive to the effects of harvest opening size, as they are most likely to be free of understorey vegetation competition.

Ecophysiology study For additional detail on the seedling ecophysiology study at Lucille Mountain, refer to Lajzerowicz (2000).

In 1997, approximately 260 seedlings each of Engelmann spruce and subalpine fir were selected along ecophysiology rows in the 40 × 40 m plots in the three silvicultural treatments. Every second experimental seedling in these rows was fertilized by hand with 25 g (application rate of 400 kg/ha) of a complete slow release fertilizer (20-6-12 N-P-K with micronutrients) at the beginning of the growing seasons in 1997 and 1998. Dosages were calibrated in consultation with local experts (e.g., R. Brockley, Kalamalka Research Station) to avoid migration of fertilizer to other locations.

In 1998 the growth environment of individual seedlings was quantified with measurements of soil temperature and growing-season light availability. Seedling measurements included height, basal diameter, aboveground and total mass of seedlings, as well as mass allocation to needles, stems, and roots. Soil analyses included extractable N, and rates of production were determined for nitrate, ammonium, and dissolved organic nitrogen (DON) in each of the three harvest treatments twice during the growing season (May–June and July–August).

Vegetation competition study Ten Engelmann spruce and 10 subalpine fir seedlings were randomly selected from vegetation competition assessment rows in two of the five field installations established in the clearcut, summer 0.2-ha patch cut, and irregular shelterwood treatments. For each seedling, percent cover, average height of the canopy, and proximity was assessed for each vegetation species that covered at least 5% of a 1.26 m radius tree-centred plot according to methods outlined in DeLong (1991). Plots were assessed 2 (1993), 3 (1994), 4 (1995), and 9 (2000) years post-harvest. From the data, a light interception index was calculated according to the equation:

$$LII = \Sigma[(C_i \times H_i)/P_i]$$

where:

i = each non-crop species that is > 5% cover and > ½ crop tree height,
C = percent cover, H = average height (cm) of competing species, and
P = proximity (dm) of competing species to crop tree (DeLong 1991).

In addition, mortality, height (cm), and root collar diameter (mm) were recorded for each tree seedling.

6.4.3 Results

Growth environment and vegetation competition Growing-season light levels determined from individual-tree measurements on the ecophysiology population were two times greater in the clearcut than in the shelterwood and one-and-a-half times greater in the clearcut than in the 0.2-ha patch cuts. Average growing-season soil temperature differed by only about 2°C among treatments (see also Section 6.1). Measurements of light availability and soil temperature were strongly and positively related with one another ($r_{ss} > 0.5$, $p < 0.05$) and with the presence of adjacent leave-trees. For instance, the coldest soil temperatures were observed in the irregular shelterwood, which coincided with the greatest amount and variation in overstorey coverage, and the clearcut had the warmest and least variable soil temperatures (Lajzerowicz 2000).

Median values of extractable mineral N in the soil were greatest in the clearcut, and in general the two partial cuts were similar. Extractable mineral N was also greater in May than July, whereas rates of mineral N production were greater in July than May. The median values of extractable DON and DON production were one to two orders of magnitude greater than mineral N and showed no difference between silviculture treatments.

Vegetation competition 2 years after harvest, as measured by Light Interception Index (LII) levels, was initially lowest in the clearcut treatment and highest in the summer patch cut. In 2000, 9 years after harvest, LII values were substantially greater in the clearcut and the summer patch cut than in the irregular shelterwood (Figure 16). The main competing vegetation species were the shrubs *Rhododendron albiflorum* and *Menziesia ferruginea*, except from 1993 until 1995 in the clearcut, where it was the herb *Epilobium angustifolium*.

The changes in LII can be largely explained by the changes in the pre-harvest dominants *R. albiflorum* and *M. ferruginea*. These species were substantially reduced during clearcut harvesting, somewhat reduced by patch cut harvest, and relatively unchanged by the winter harvesting in the irregular shelterwood. They then recovered over the next 7 years to levels that were likely equal to or above pre-harvest levels. In the clearcut, *E. angustifolium* became established on exposed mineral soil and provided some competition in the early years before *R. albiflorum* and *M. ferruginea* were able to recover.

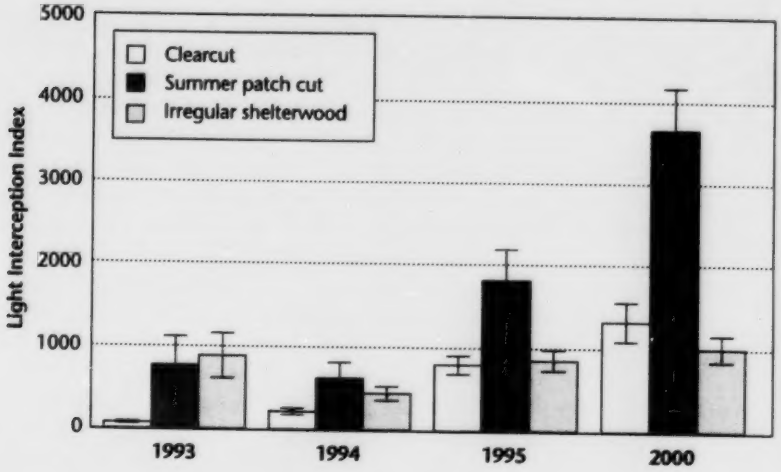

FIGURE 16 *Light Interception Index by year for clearcut, summer patch cut, and irregular shelterwood treatments (mean ± 1 SE).*

Survival, damage, and mortality of permanent sample trees In the first year following planting, the mortality of both spruce and subalpine fir was low, ranging from 0 to 0.7% for spruce, and from 1.1 to 2.6% for subalpine fir. There were no significant differences among silvicultural treatments ($p<0.01$).

First-year frost damage to the foliage or buds of the seedlings varied by species, and for spruce, by silvicultural treatment.

For Engelmann spruce, treatments with the highest amount of overstorey shelter and least open sky had the least apparent frost damage, while the most open treatments had the highest amount of damage (Figure 17). Based on data pooled by treatment, apparent frost damage rates in all treatments were significantly different ($p<0.01$). For spruce, frost is the most likely damage agent, because the observations recorded are consistent with general field observations following severe -5 and -6°C frost events in late summer of 1992.

For subalpine fir, incidence of bud and foliage damage appears to be inconsistent with frost occurrence, and was relatively high in all harvest treatments, ranging from 39.1% in the irregular shelterwood to 42.1% in the patch cut and 33.4% in the clearcut, with no significant differences among treatments ($p<0.01$). Unlike spruce, first-year damage to subalpine fir showed no relationship to differences in overstorey shelter or open sky in the three silviculture treatments. Overwinter damage to subalpine fir foliage, rather than frost, may explain the observed damage to this tree species. Fir-fireweed rust (*Pucciniastrum epilobii* Otth.) also produces patchy browning-off of foliage on subalpine fir that is similar in appearance to frost damage (Bauman and Wegitz 1972). Endemic levels of needle cast on subalpine fir have been frequently observed at the Lucille Mountain site. This damage agent is believed to have little effect on seedling growth or vigour.

Seven-year seedling survival rates for planted spruce seedlings varied significantly by silvicultural treatment, and in the clearcut treatment, long-term spruce seedling survival rates (from 1992 to 1998) were significantly influenced by first-year frost damage.

Seven-year survival of non–frost-damaged spruce seedlings were 91.5, 82.5, and 65.0% in the clearcut, patch cut, and irregular shelterwood treatments, respectively. Seven-year spruce seedling survival rates in the clearcut and patch cut were not significantly different ($p<0.01$) from each other; however, 7-year survival rates of spruce seedlings in the irregular shelterwood were significantly lower than in either the clearcut or patch cut ($p<0.01$).

In the clearcut, 7-year survival of frost-damaged spruce seedlings (72%) was significantly lower ($p<0.01$) than survival of seedlings without 1992 frost damage (91.4%). No significant differences ($p<0.01$) between frost-damaged and undamaged spruce seedlings were found in either the 0.2-ha patch cut or the irregular shelterwood treatment, possibly because sample sizes of frost-damaged seedlings were small.

Seedling growth and responses Results of seedling growth for the two seedling study populations are presented separately due to differences in analytical approaches. In this analysis, seedlings in the permanent sample population were post-stratified after measurement of the entire seedling population to assess the response of the tallest 700 sph (55%) of the planted stock. In contrast, the ecophysiology population includes all seedlings sampled in this study population in the three harvest treatments.

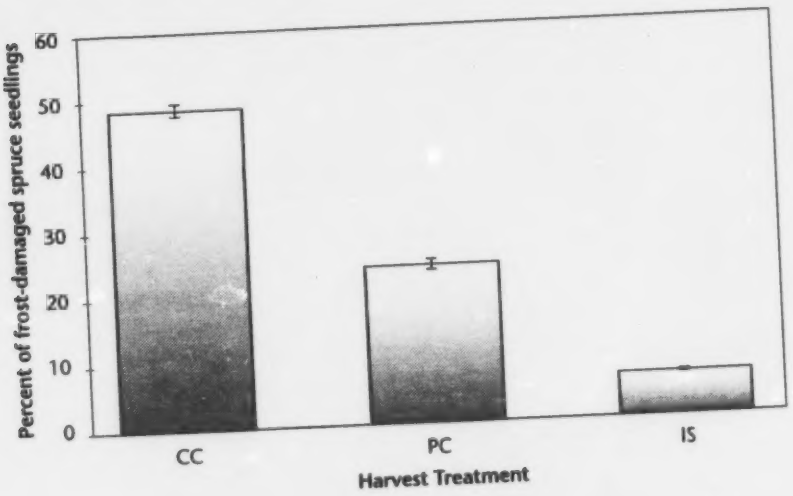

FIGURE 17 *Percentage of Engelmann spruce seedlings damaged by frost 1 year after outplanting in the clearcut (CC), patch cut (PC), and irregular shelterwood (IS) treatment units (mean ± 1 SE). Data pooled by treatment.*

Permanent sample population Seven-year total height and current leader growth of the top 700 sph of Engelmann spruce and subalpine fir seedlings were substantially reduced in the irregular shelterwood relative to the clearcut and 0.2-ha patch cut (Figures 18 and 19). For example, for spruce, average seedling height of the largest 700 sph was 53.0 cm, 59% of the average height achieved in the clearcut; for subalpine fir, average seedling height of the largest 700 sph was 74.7 cm, 71% of the clearcut average height. The 1998

leader growth of spruce and subalpine fir in the irregular shelterwood treatment was 37% (5.2 cm) and 48% (10.8 cm) of growth on seedlings in the clearcut, respectively. Statistical comparisons of, and standard errors for, these means were not determined, as the 700 sph sub-population is not a random sub-sample of the total sample population.

For the 0.2-ha patch cuts, treatment effects on growth are potentially confounded by elevation differences; the patch cut treatment is located approximately 20–150 m in elevation below the clearcut and shelterwood treatments. This may account for the few differences observed in performance of top seedlings between the 0.2-ha patch cut and clearcut treatments. For spruce, average seedling height of the top 700 sph in the patch cut treatment was 83% of that in the clearcut. In contrast, average seedling growth of subalpine fir top trees in the patch cut was 104% of that in the clearcut. Current 1998 leader growth increments of spruce and subalpine fir in the 0.2-ha patch cut were 78% and 98% of clearcut growth increments, respectively.

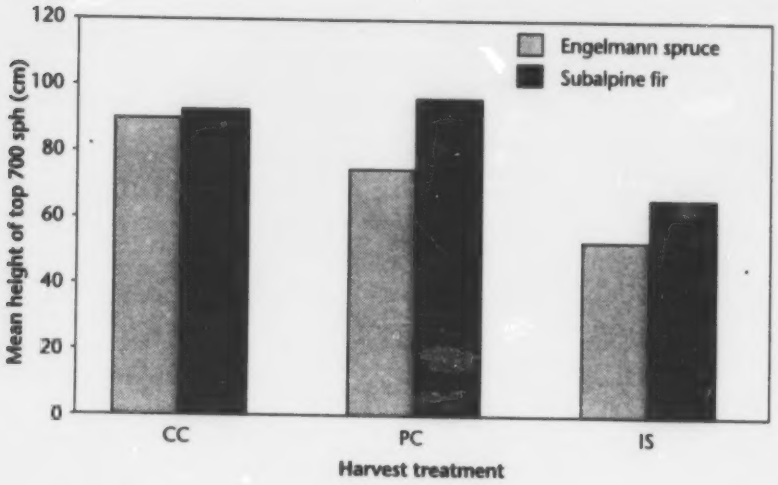

FIGURE 18 *Mean height (cm) of the top 700 sph of spruce and subalpine fir planted seedlings in the clearcut (CC), patch cut (PC), and irregular shelterwood (IS) treatment units. Seedlings were planted 7 years previously.*

Ecophysiology population The following results are summarized from Lajzerowicz (2000).

The ecophysiology population, like the top 700 sph, showed large differences in seedling growth between the three silvicultural treatments. Height and basal diameter of seedlings of both species in the clearcut were almost twice those of seedlings in the shelterwood, and subalpine fir seedlings were generally larger than Engelmann spruce. On average, total aboveground mass of seedlings doubled from the shelterwood to the patch cuts, and doubled again from the patch cuts to the clearcut. The ecophysiology study indicates that there are much greater effects of the different silvicultural treatments based on total aboveground biomass accumulation of seedlings than on height growth alone. These results suggest that height growth by itself

may be a relatively poor indicator of treatment effects on regeneration vigour, especially for subalpine fir.

In addition to the average harvest treatment effects, proximity of residual tree boles within the partial cuts had large local effects on seedling size and growth; both species showed a decline in growth within 5 m of tree boles. Root growth in these areas was especially poor, and declined strongly near mature retention trees. Engelmann spruce seedlings were more strongly suppressed than subalpine fir seedlings within 2 m of retention tree boles.

Fertilization did not have a significant effect on any of the growth parameters measured (basal diameter, height, and aboveground biomass) for either species. However, fertilizer marginally increased foliar N concentrations of both species.

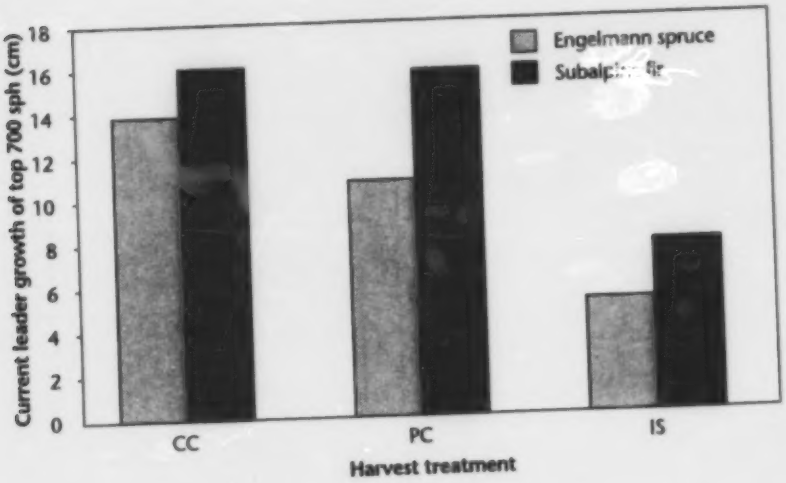

FIGURE 19 *Current annual leader growth (cm) of the top 700 sph of spruce and subalpine fir planted seedlings in the clearcut (CC), patch cut (PC), and irregular shelterwood (IS) treatment units. Seedlings were planted 7 years previously.*

Seedling response to light conditions and soil temperature For the ecophysiology population examined in this sub-project, height, diameter, and ring width increment were all highly correlated with measurements of light availability and soil temperature ($r_{xy}>0.5$, $p<0.05$ for both variables). Using a multiple linear regression, we were able to explain almost half of the total variation in growth of seedlings of both species by using these two variables as predictors (Lajzerowicz 2000).

Vegetation competition levels had a negative effect on seedling performance. As LII increased, the maximum root collar diameter achieved after 9 years decreased for both subalpine fir and Engelmann spruce (Figures 20 and 21). No Engelmann spruce seedlings survived above an LII of 5060, while there was survival of subalpine fir up to an LII of 7800. The effect of tree canopy light interception on spruce growth was evident because all trees from the irregular shelterwood are grouped near the bottom of the y or "growth" axis (Figure 21). This effect was not as clear for subalpine fir (Figure 20).

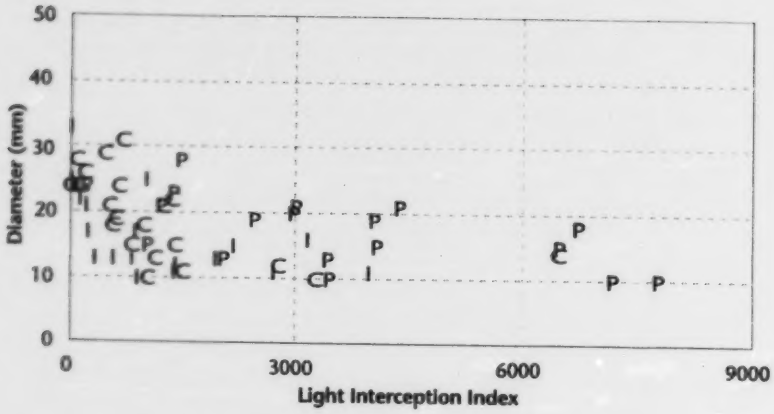

FIGURE 20 *Light Interception Index by root collar diameter (mm) for subalpine fir. C = clearcut, P = summer patch cut, and I = irregular shelterwood.*

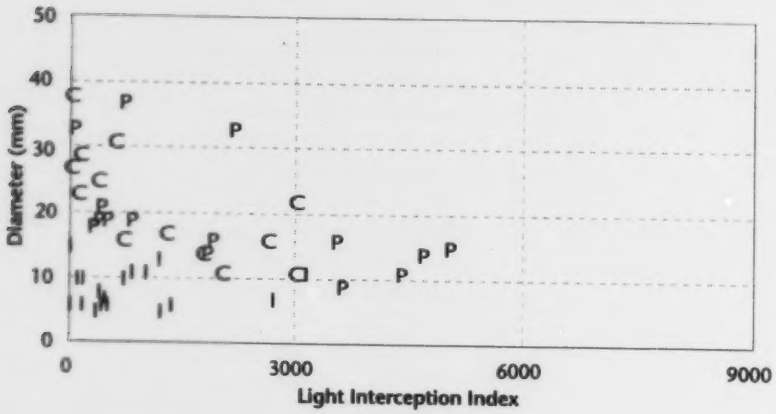

FIGURE 21 *Light Interception Index by root collar diameter (mm) for Engelmann spruce. C = clearcut, P = summer patch cut, and I = irregular shelterwood.*

6.4.4 Discussion Our results suggest that residual canopy retention in partial cut silvicultural systems may have pronounced effects on growth of planted seedlings in ESSF forests. In ESSF forests, canopy retention results in lower light and temperature environments for seedlings relative to open areas such as clearcuts. This situation results in a relative reduction in growth performance of planted seedlings in areas with significant overstorey retention compared to clearcut areas or other relatively open harvested areas with little or no retention. Given the cold climate of the ESSF, light and low temperature conditions (air and soil) are generally the two most important factors for growth (Chapin 1983; Körner 1998).

Both spruce and subalpine fir showed relatively higher growth in treatments with less overhead canopy retention. For planted regeneration, this corresponded with a decrease in canopy retention and an increase in light

and temperature. Maximum potential seedling diameter was also found to drop with increasing levels of LII, an indirect estimate of light availability. Several studies have shown similar responses when seedlings were grown in open light compared to shaded conditions (Elliot and White 1984; Lopushinsky and Max 1990) and vegetation competition for light (Wright et al. 1998).

The difference observed in response of spruce and subalpine fir to residual canopy cover could reflect interspecific differences in shade tolerance. The observation that differences in leader growth were more extreme than differences in total height suggests that treatment differences in seedling vigour will increase over time.

Differences in mean growing-season soil temperatures between harvest treatments were significant, but small in absolute terms. Data from a separate greenhouse study under controlled soil temperatures (C. Lajzerowicz and M. Walters, unpublished data, 1999) suggest that the range of soil temperatures measured at the Lucille Mountain site during the active growing season is limiting for seedling growth. Data collected on mean growing-season air temperature (Figure 5, Section 6.1) are not in the range considered to be limiting to growth. Also, the lack of growing-season frost events on this site suggests that, during the growing season, soil temperature rather than air temperature may be the more important factor influencing growth. Low soil temperature influences many physiological processes important for growth and development of seedlings (Körner 1998).

Proximity to mature tree boles also had strong effects on growth of seedlings, since seedlings within 5 m of mature trees were much smaller than those more distant. Root growth and root mass were dramatically affected by planting close to retention trees and may contribute to the differences in growth between the partial cut treatments and the clearcut.

At this site, subalpine fir appears to be more tolerant of low light and low soil temperatures than Engelmann spruce. For instance, the greater tolerance of subalpine fir to higher competition levels as expressed by LII values may be partially attributed to its tolerance to lower soil temperatures. These results are corroborated by the Quesnel Highland group selection silvicultural systems research trial in the Cariboo Forest Region, where subalpine fir had higher survival than spruce in the smaller openings (0.13 and 0.03 ha) (Newsome et al. 2000). The higher tolerance of subalpine fir to more extreme conditions is not a new idea, because the proportion of subalpine fir in the canopy has been found to increase with both elevation and latitude in the ESSF (Klinka et al. 1996).

The low LII values in the clearcut 2 years after harvest likely relate to reductions in plant cover associated with summer harvest. Plant cover was low in the vegetation succession plots within the clearcut as well. The rate of increase in LII over the 9 years in the different silvicultural systems corresponds well with the measurements of the light environment. The higher light levels in the clearcut and summer patch cut due to total canopy removal resulted in a larger plant cover response over time than in the irregular shelterwood, where light levels would not have increased to the same degree (see Section 6.1). The differences in LII between the clearcut and the summer patch cut likely relates to the larger amount of soil disturbance associated with harvesting in the clearcut, which meant that competing vegetation had to establish from seed rather than regenerate from existing shoot or root matter.

Soil N mineralization rates were similar, and extractable inorganic N pools in the soil were higher than those reported in other conifer-dominated and/or cold systems (Matson and Boone 1984; Zak et al. 1994; Chappell et al. 1999). These results, combined with the unresponsiveness of seedling growth to N fertilization, suggest that soil N availability is not limiting seedling growth at this site.

Given the inherent ecological limitations to seedling establishment and growth in the ESSF zone demonstrated in this study, foresters should re-examine their assumptions about appropriate planting sites and stocking standards on ESSF sites. Seedlings should be planted only in favourable areas or microsites where acceptable growth, relative to ecologically based regeneration assessment criteria, can be expected. Our findings suggest that, within partial cuts:

1. planting should occur in the more open areas, preferably more than five m from leave-trees or edges;
2. subalpine fir may be favoured over Engelmann spruce in areas very close to mature retention trees; and
3. managers should place increased (though not exclusive) reliance on acceptable advance regeneration, retained overstorey trees, and natural regeneration for meeting stand management goals, including timber management goals.

Where use of planting in ESSF partial cuts is necessary for administrative or silvicultural reasons, several approaches are recommended:

1. Concentrate planting in areas where the overstorey density is reduced, or where larger openings have been created. In some cases, planting may be delayed until after the second stand entry.
2. Locally test a range of harvest opening sizes to determine where, and how long after harvest, acceptable seedling performance occurs.
3. Rely on natural regeneration and advanced regeneration in conjunction with planting, both as a cost-reducing measure and to mitigate silvicultural risk of a single regeneration strategy.

6.5 Stand Development and Growth following Partial Cutting

MIKE JULL

Key Results

Individual Leave-tree Responses

- For individual leave-trees, basal area increment after partial cutting was positively correlated with initial tree diameter. In general, the bigger the tree, the larger the basal area increment.
- Seven-year diameter growth of residual spruce and subalpine fir leave-trees ranged from 1 to 6 cm, typically averaging about 0.25–0.6 cm/yr.
- There were no consistent differences between spruce and subalpine fir in basal area or diameter response following partial cutting.
- There was no consistent post-harvest height growth release following the partial cut.

Stand-level Responses

- Post-harvest stand growth rates (as measured by gross basal area increment per hectare) had a strong positive correlation with initial post-harvest stand basal area. Differences in stand structure among treatments had no apparent effect on this relationship.
- During the first 7 years, gross growth of leave-trees in the partial cut treatments was often offset by mortality losses from windthrow and other losses. Over all treatments, there was an average 6% net loss of basal area, primarily due to 1996 windstorms. However, this trend also varied by treatment; there was a net loss of 11 and 12% of the initial basal area in the single-tree selection and irregular shelterwood treatments, respectively, and a net gain of 10% in the group retention treatment.

6.5.1 **Objectives** The objectives are to compare post-harvest growth, survival, and mortality of residual leave-trees by species and size classes in a range of partially cut stand structures. Responses were assessed at both the tree and stand level.

6.5.2 **Methods** Twelve 30 × 60 m (0.18 ha) growth-and-yield permanent sample plots (PSPs) were established in fall 1992, in each of four replicates of the three partial cut treatments (group retention, irregular shelterwood, and single-tree selection). Plots were installed using established procedures (B.C. Forest Productivity Council 1990). Plot size was chosen to include an average initial sample size per plot of at least 50 residual trees greater than 4.0 cm dbh. Trees were tagged individually at breast height (1.3 m above point of germination). All plots were remeasured in early June of 1996 and 2000 (three and seven growing seasons after plot establishment, respectively).

Data analyses summarized plot data at each measurement period by tree, plot, and treatment unit. Key response variables examined included periodic changes in tree diameter, height, and basal area, at a tree and stand level. Volume trends were not examined in this analysis.

Analyses of individual-tree growth responses and stand-level gross basal area increment responses after treatment were based on data from all surviving trees in the sample populations. These included all trees that were

1) >4 cm dbh and alive in both 1992 and 2000, or 2) less than the measurement limit of 4 cm dbh in 1992 but larger than 4 cm dbh and still alive in 2000. These are referred to as "surviving trees" in the following section. Trees that had died standing or been wind-damaged (uprooted or windsnapped) between 1992 and 2000 were thus excluded from this portion of the analysis.

Net stand-level responses to the treatments were determined by subtracting stand mortality losses from gross growth.

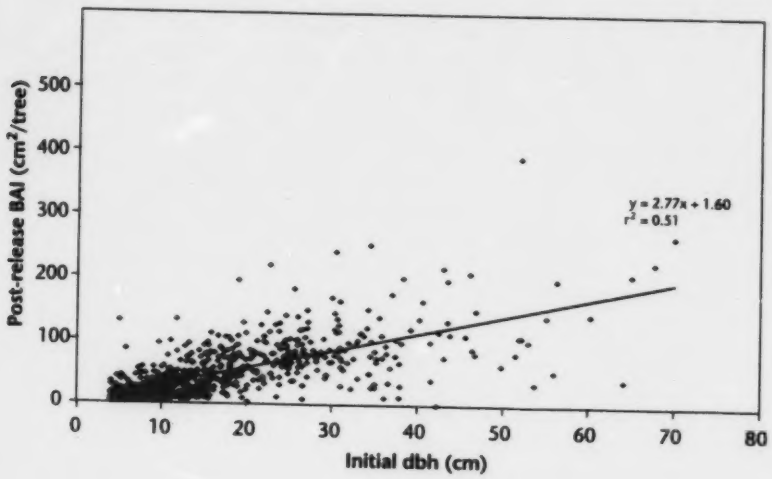

FIGURE 22 *Relationship of the basal area increment (BAI) of individual leave-trees 7 years after partial cutting to the initial post-harvest tree diameter at breast height (dbh).*

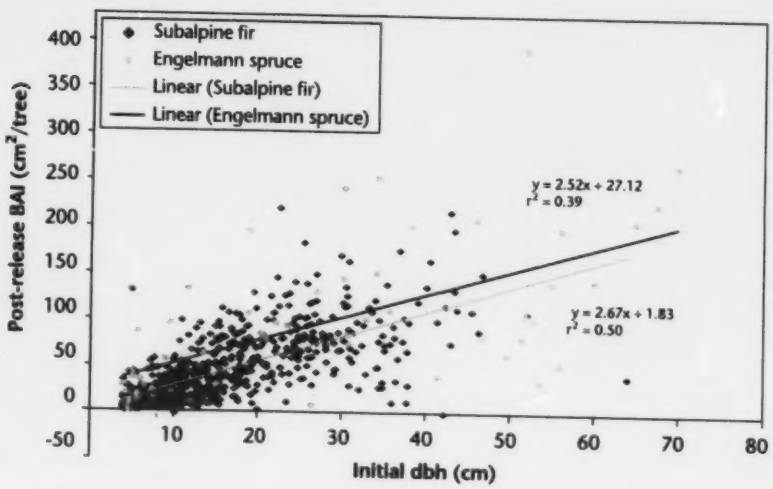

FIGURE 23 *Comparison of the basal area increment (BAI) of individual Engelmann spruce and subalpine fir leave-trees 7 years after partial cutting relative to initial post-harvest tree diameter at breast height (dbh).*

6.5.3 Results

Individual-tree growth responses Seven-year post-harvest basal area increment (BAI) or growth of residual leave-trees was positively correlated with tree diameter ($p<0.01$, $r^2=0.51$), as shown in Figure 22. BAI of leave-trees had no apparent relationship to silvicultural treatment, suggesting that leave-tree BAI is insensitive to the differences in stand structure created by the three treatments.

There appeared to be no significant difference in the BAI response between spruce and subalpine fir (Figure 23). Basal area increment of Engelmann spruce was more variable than that of subalpine fir, and, for spruce, less of the variation was explained by differences in tree size ($r^2 = 0.387$ for spruce vs. $r^2 = 0.502$ for subalpine fir). While initial post-harvest tree diameter explains about 51% of the observed variability in basal area increment for both species combined, other factors may have a significant influence. Such potential factors may include differences in spatial relationships and competitive positions of trees relative to their neighbours, relative positioning of trees within gaps and clumps, or microsite variability.

Total 7-year diameter growth rates of surviving residual trees were typically 1–6 cm, averaging about 0.25–0.60 cm/yr over 7 years (Figure 24). Compared to basal area increment, diameter growth was more poorly correlated with tree size.

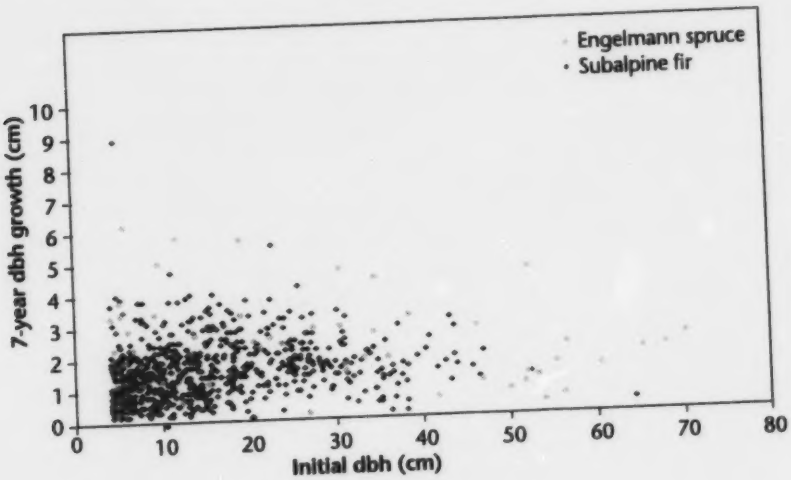

FIGURE 24 *Seven-year post-release diameter growth relative to initial tree diameter at breast height (dbh) following partial cut harvesting, for spruce and subalpine fir.*

Stand-level responses Within the range of initial post-harvest basal areas of leave-trees surviving from 1992–2000 across all plots (5–18 m^2/ha), post-harvest stand-level gross basal area increment (GBAI) was positively correlated with initial basal area ($p<0.01$, $r^2=0.71$) (Figure 25). Consistent with trends for tree-level BAI, stand-level GBAI also appeared to be unrelated to silvicultural treatment and consequent differences in stand structure. The regression in Figure 25 is therefore based on combined data from all three partial cut treatments. A linear relationship for this regression was also examined, but had a lower r^2 than the natural logarithmic relationship. A logarithmic relationship is also more reasonable from a biological perspective, because stand-level growth parameters tend to approach the asymptote as full basal area or site occupancy is reached (Langsaeter 1941; Möller 1947).

Current periodic rate of 7-year GBAI ranged from approximately 1.3 m^2/ha at an initial basal area of 6 m^2/ha to 2.2 m^2/ha at an initial basal area of 18 m^2/ha. These correspond to average annual growth rates of 0.19 and 0.31 m^2/ha/yr, respectively, in this first 7 years.

Overall, during this period, mortality losses from windthrow and other losses offset stand-level growth in the partial cut treatments. Over all treatments, there was an average 6% net reduction in stand basal area between September 1992 and June 2000. Reductions in basal area values in some plots and treatments between the June 1996 and June 2000 remeasurements were primarily due to windthrow during a severe August 1996 windstorm. Differences among the different treatments were masked by high variability among sample plots, but general trends are evident (Table 9). In two of the treatments, single-tree selection and the irregular shelterwood, post-harvest windthrow losses and other mortality during this period exceeded gross basal area growth, resulting in a modest net decrease in stand basal area after 7 years of 12 and 11%, respectively. Conversely, in the group retention treatment, gross growth exceeded mortality, resulting in a net increase of 10% in stand basal area.

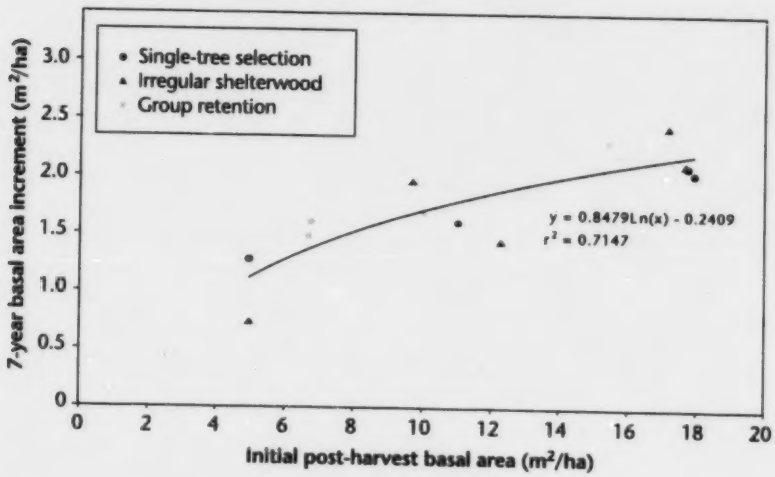

FIGURE 25 *Relationship of stand basal area increment 7 years after partial cutting to initial post-harvest stand basal area.*

6.5.4 Discussion Due to the reduction in stand density resulting from the partial cutting treatments, residual trees have grown in more open stand conditions than existed before the harvest. Height growth response has lagged and no consistent trends were apparent up to 8 years following harvesting. There were no consistent differences in the diameter or basal area growth response of Engelmann spruce and subalpine fir in these partially cut treatments.

These findings are consistent with other studies of subalpine fir advance regeneration response in cutover stands in the moist to wet ESSF zone elsewhere in eastern British Columbia, and in the central Rocky Mountains of the United States. In the North Thompson area of British Columbia, Herring (1977) found that delays in radial diameter growth release after harvest were commonly 1–2 years, while height growth delays were 3–5 years. However, following the initial delay period, the advance regeneration is capable of excellent growth performance, with the major factors affecting growth being tree competition and site quality. Similarly, in a replicated study in subalpine spruce-fir forests of Idaho, Wyoming, and Utah, McCaughey and Schmidt (1982) examined advance regeneration response under a range of harvest intensities and degrees of overstorey retention from partial cuts to clearcut. Diameter growth response occurred about 3 years after the harvest, while height growth was found to have a response delay of 7 years or more after release. Advance regeneration response of spruce and subalpine fir differed very little. However, growth release of both species was negatively affected by the density of the residual overstorey.

The greater basal area response of individual large-diameter trees relative to small trees (and similar diameter growth of large trees relative to smaller

TABLE 9 *Summary of standing basal area (BA) of live trees by treatment and sample plot location at three sequential measurement dates, 1992–2000, following partial cut harvesting at Lucille Mountain (GR=group retention, IS=irregular shelterwood, ST=single-tree selection)*

		September 1992		June 1996		June 2000	
Treatment	Plot #	BA/ha (m^2)	% of initial BA	BA/ha (m^2)	% of initial BA	BA/ha (m^2)	% of initial BA
GR	1	7.15		7.72		8.12	
GR	3	16.12		17.14		17.70	
GR	9	10.70		10.84		11.72	
GR	15	7.50		7.40		8.34	
Mean GR BA/ha		10.37	(100)	10.78	104	11.47	110
IS	2	18.97		19.32		19.84	
IS	5	15.52		16.19		13.72	
IS	7	12.00		12.75		11.69	
IS	13	10.48		10.06		5.71	
Mean IS BA/ha		14.24	(100)	14.58	102	12.74	89
ST	4	18.91		19.67		19.61	
ST	6	18.12		19.21		19.97	
ST	10	13.67		13.32		6.23	
ST	11	15.85		16.27		12.65	
Mean ST BA/ha		16.64	(100)	17.12	103	14.62	88
Overall mean BA/ha		13.75	(100)	14.16	103	12.94	94

trees) at Lucille Mountain appears to contradict common management assumptions (e.g., Alexander, 1987) about the limited future growth potential of mature leave-trees in ESSF partial cuts. However, vigorous release of 30–60 cm dbh spruce and 20–40 cm dbh subalpine fir after selection and diameter-limit partial cuts has been observed in wet cool SBSwk1 spruce-fir forest types at the Aleza Lake Forest east of Prince George (Jull and Farnden, in prep.).

The positive correlation between post-harvest BA1 and initial tree diameter suggests that an individual leave-tree in a partial cut stand continues to maintain a degree of site occupancy or "effective growing space" in the stand that is roughly in direct proportion to its size. As seems intuitively obvious, the larger the tree diameter, the greater the growing space occupied. As tree height is well correlated with tree diameter in the Lucille Mountain partial cut treatments, large-diameter trees in the stand also have a superior competitive position relative to smaller trees. This is especially the case in the clumpy stand structures common in many ESSF forest types. These conclusions have clear implications for the setting of appropriate regeneration strategies, stocking standards, and stand management goals in the ESSF.

As previously discussed, the initial drop in basal area stocking after partial cutting at Lucille Mountain was due to the cumulative effects of harvesting-related mortality, including windthrow and some standing leave-tree mortality. Similar trends of attrition of partial cut stands, and decrease in basal area and volume for about a decade after partial cutting, have been noted by many other studies of subalpine and sub-boreal spruce–subalpine fir forest types (Barnes 1937; Fraser and Alexander 1949; Alexander 1956; Stettler 1958; Glew 1963; Roe and DeJarnette 1965).

However, it would likely be a mistake to extrapolate this trend into the future. As the partial cuts continue to recover from harvesting disturbances, net basal area growth will likely become positive. This would be due to the cumulative effects of accelerating growth release of residual trees, increasing regeneration ingress, and expected reduction in windthrow losses over time. The degree of periodic wind damage experienced in the first 5 years following partial cut harvesting is likely to lessen over time as the leave-trees acclimatize to the more open conditions and become more windfirm.

Basal area and diameter growth response of the leave-trees in the Lucille Mountain partial cuts during the first 7 years provides a minimum estimate of expected longer-term growth rates in these stands. For the first several years after partial cutting, residual trees may be rebuilding foliage and crown area lost due to previous competition and suppression, and replacing the foliage lost from logging damage. Likewise, the roots and crowns of residual trees and new regeneration take time to recapture the above- and belowground resources and growing space vacated by harvested trees. In the ESSF, this stand recovery process is likely to be relatively slow, suggesting a significant lag time between an initial partial cutting and achievement of peak stand-level growth rates. Some anecdotal evidence supports this hypothesis. For example, while initial post-harvest basal area increment rates in the first 7 years at Lucille Mountain ranged from 0.15 to 0.30 m^2/ha/yr, Bergstrom (1983) found that cutover ESSF stands sampled 30–40 years after diameter-limit logging in the Adams Lake area had mean annual basal area increments of 0.76 m^2/ha/yr. This hypothesis is further supported by data from long-term permanent plots in partial cut interior spruce (*Picea glauca* x *engelmannii*)–subalpine fir stands in the SBSwk1 variant at the Aleza Lake

Research Forest (Barnes 1937; Fraser and Alexander 1949; Jull and Farnden, in prep.); here, annual basal area increment lagged for the first 5–10 years after harvest, and then increased until stands approached 25–30 m^2/h, when BAI reached its maximum.

In residual stands, stand-level basal area growth rates following partial cutting are directly related to the amount of well-distributed basal area retained on the site. However, absolute rates of basal area regrowth after partial cutting in the ESSF are still quite low, and at Lucille Mountain, it will take several decades (40–60 years) for post-harvest basal areas in the partial cuts to return to pre-harvest levels. Lower post-harvest basal areas will take longer to return to pre-harvest levels. Faster initial basal area growth rates following partial cutting can be facilitated by prescribing adequate post-harvest basal area and stand structural targets, so that leave-trees within partial cut stands can more rapidly and efficiently re-occupy growing space vacated by harvested trees. This recommendation is supported by the relationship between residual basal area density and stand-level basal area increment observed at the Lucille Mountain trial. Extrapolating this relationship beyond the existing range of data suggests that stand basal area growth rates may be maximized at basal area stocking levels greater than 20 m^2 per hectare. Nevertheless, it may not be possible, or at least practical, to prescribe for maintenance of optimum levels of growing stock in ESSF stands, while simultaneously trying to establish regeneration underneath the same stand.

6.6 Wind and Windthrow Incidence

MIKE JULL AND
BOB SAGAR

Key Results

- The Lucille Mountain trial site has high topographic wind exposure. Maximum wind gusts usually exceeded 72 km/hr several times each year, and exceeded 100 km/hr in one winter storm.
- Incidence of wind damage (uprooting and windsnap) was 6, 10.3, and 8.6% of stems in the group retention, irregular shelterwood, and single-tree selection treatments respectively. Most of this was due to two 1996 wind events in which peak gusts ranged from 90 to 105 km/hr.
- Along windward clearcut edges (south- and west-facing) following the same 1996 windstorms, wind damage incidence was 8.8% of stems within 40 m of the edge. Wind damage was most severe (11.4–14.7%) within the first 20 m of the harvest boundary, and lower (4.4–5.6%) beyond 20 m.
- Intermediate tree classes (diameters ranging from 17.5 to 37.5 cm) had a higher risk of wind damage in these ESSF partial cuts than other size classes.
- Dominant and strongly codominant trees (>40 cm dbh) had low to moderate risk of wind damage in these ESSF partial cuts, relative to intermediate classes.
- The predominant direction of damaging winds was southwest to west.

6.6.1 **Objectives** The objectives are to examine:

- incidence and severity of high-wind events at the Lucille Mountain site; and
- post-harvest windfirmness or wind damage to residual trees by species and size class in group retention, single-tree selection, and irregular shelterwood treatments, and along clearcut edges.

6.6.2 **Methods** Wind speed and direction are measured by an anemometer mounted on a 9.8-m (30-ft) tower in the centre of the clearcut. A Wind Monitor (RM Young, Traverse City, Mich., Model 05130) was mounted on a horizontal 1.2-m pipe attached to the top of the tower in June 1995. Data are recorded by a computerized datalogger (Campbell Scientific Ltd., Edmonton Alta., Model CR10 or CR10X) and storage module (Campbell Scientific Ltd. Model SM-716-55). Wind data are reported here for 4 years or ± 1600 days of monitoring.

Windthrow monitoring is conducted once annually in all treatments, generally in July or early August of each year. In the case of severe wind events, as in 1996, monitoring is conducted more frequently.

In the partial cut treatments, twelve 30 × 60 m (0.18 ha) growth-and-yield permanent sample plots (PSPs) were established in fall 1992, in each of four replicates of the three partial cut treatments, following conventional procedures (B.C. Forest Productivity Council 1990). A total of 0.72 ha, or 18% of the area, is monitored in each of the three treatment units. For each damaged or windthrown tree >20 cm dbh sampled, we recorded total height, diameter, species, type of wind damage (windthrow or windsnap), location or height of windsnap (if any), direction of tree fall (top to roots, indicating the direction from which the damaging wind came), rooting characteristics, height to diameter ratio, crown characteristics, and pathological remarks. In addition to annual windthrow monitoring, plots were fully remeasured in 1996, and will be remeasured periodically at approximately 5-year intervals.

Along clearcut edges, windthrow monitoring procedures are similar, except that the plots are replaced by a continuous 40-m-wide belt transect in the standing timber immediately surrounding the clearcut. Each damaged or windthrown tree encountered is tagged, data are recorded in the same manner as in the partial cut plots, and distance from the harvest boundary is recorded. Belt transect sampling allows easy conversion of windthrow data to per-hectare statistics. A total of approximately 2000 m (8 ha) of clearcut perimeter are monitored.

6.6.3 **Results and discussion** Due to the limited treatment replication, small treatment size, potential edge effect, lack of geographic replication, and inherent high variability of wind and windthrow phenomena, we present only descriptive data. While we believe these results to be useful in interpreting treatment outcomes at Lucille Mountain, and as exploratory data for examining wind patterns and windthrow effects, caution should be exercised in extrapolating treatment differences and results to other stands and sites.

High-wind events The peak wind speeds reported (following) are based on maximum wind speeds observed in the highest 1-minute wind run during each 24-hour period. Characterization of peak wind regimes in an area is useful for assessing windthrow risk.

This is the wind summary for the Lucille Mountain wind station, 1 July 1995 – 7 October 1999 (maximum wind speeds are based on highest 1 minute wind run during the 24-hour period:

Number of days observed	1418	
Mean wind speed (km/hr)	10.08	
Number of days with 1-minute max. wind speed >36 km/hr	179	(12.6%)
Number of days with 1-minute max. wind speed >50 km/hr	13	(0.9%)
Number of days with 1-second wind gusts >72 km/hr	11	(0.8%)

Lucille Mountain is very windy, due to its location on an exposed mountain ridge adjacent to a narrow valley on the windward side of the ridge. At Lucille Mountain, 13.8% of days (or 50 days per year) had peak wind speeds exceeding 10 m/s (36 km/hr). Daily maximum wind speeds exceeded 15 m/s (54 km/hr) approximately 4–5 days per year, on average.

The Lucille Mountain wind station also records 1-second wind speed and direction data when a 1-second wind speed exceeds 20 m/s (72 km/hr). These 1-second wind speed maximums greater than 20 m/s are referred to as "peak wind gusts." Between June 1995 and October 1997, a total of eight peak wind gusts were recorded (Table 10). Frequency of days with these peak wind gusts was 0.96% of recorded days. The highest 1-second wind gust speeds measured to date were 27.65 m/s (100 km/hr) and 28.47 m/s (103 km/hr) on 12–13 January 1996, and were probably part of the same storm system overlapping two daily reporting periods. A 30 August 1996 peak gust event measured 24.78 m/s (89 km/hr). Peak wind gust events were almost exclusively southwesterly to westerly. Peak 1-second wind gust speeds typically exceed daily 1-minute maximum wind speeds by 45–50%.

TABLE 10 *Summary of 1-second peak wind gust events for the Lucille Mountain site, 1 July 1995 – 7 October 1999*

Date	Maximum 1-minute wind speed(m/s)	1-second peak gust speed (m/s)	Direction of peak wind gust	Prevailing storm wind direction	Ratio of 1-second peak gust speed to 1-minute wind run speed
18-Nov-95	16.4	22.6	SW	SW	1.38
12-Jan-96	17.2	28.5	W	SW	1.66
13-Jan-96	18.2	27.7	SW	WSW	1.53
15-Mar-96	15.5	21.8	W	WSW–WNW	1.40
15-Jun-96	16.5	21.1	SSW	SW	1.28
30-Aug-96	18.4	24.8	SW	SW	1.35
06-Aug-97	15.1	22.5	SSW	SSW–WSW	1.49
01-Sep-97	16.1	21.9	SSW	SSW–WSW	1.36
11-Jan-99	15.1	21.4	NNW	NW–NNW	1.42
12-Jan 99	15.8	21.9	W	SW–W	1.39
Mean					1.43

Note: 1 m/s = 3.6 km/hr.

How representative are the frequency and magnitude of the wind events and peak gusts reported at Lucille Mountain compared to long-term patterns typically experienced in this region? Murphy and Jackson (1997) examined more than 30 years of peak wind gust data from four central interior airport locations, finding that 78% of monthly peak gusts are between 50 and 90 km/hr. A peak gust speed of about 70 km/hr is estimated to occur in all these locations about once annually, on average (calculated return interval of 1.01–1.44 years). A peak gust speed of 90 km/hr is estimated to occur on average return intervals of 1.58 years for Prince George to 5.50 years for Quesnel airport. Estimated return periods for 110 km/hr peak gust speeds are considerably longer, ranging from 6–7 years (Prince George and Smithers) to 26 years (Quesnel), and up to 39 years (Williams Lake).

Wind damage following harvest treatments Because wind events are clearly both frequent and intense at the Lucille Mountain site, it is not surprising that some wind damage to stands has occurred both at the margins of the clearcut treatment, and in the three partial cut treatments. Two or more high-wind events ranging from 90 to 105 km/hr were observed at this site, including high winds on 12–13 January 1996 and 30 August 1996. These wind events are responsible for most of the stand wind damage that has occurred at Lucille Mountain since trial establishment. Little or no wind damage has been observed in other years. Wind losses for the partial cut treatments for the 7 years since harvest are summarized by treatment in Table 11.

TABLE 11 *Summary of percent wind damage by treatment*

	Group retention	Irregular shelterwood	Single-tree selection
% wind damage by stems per ha	6.0	10.3	8.6
% wind damage by residual basal area	4.0	12.1	15.0

Orientation of windthrown trees on the site was predominantly southwesterly in origin, with a minor westerly component (Figure 26). This is consistent with the observed direction of maximum daily wind speeds and peak gusts on this site. In addition, this is consistent with longer-term wind data from Prince George (Murphy and Jackson 1997), where 87.4% of monthly gust extremes over a 50-year period were southerly to westerly in origin.

Wind damage along clearcut edges Most of the 1996 wind damage along clearcut edges occurred along windward (south- and west-facing) clearcut edges. Therefore, for both reasons of management significance and available sample sizes, this analysis will focus on windward edges. Based on 1996 wind damage patterns, trees within the first 20 m of the clearcut boundary along the windward edges took the brunt of the damage (Figure 27). Based on a pre-harvest average density of 346 sph >20 cm dbh, 1996 wind damage rates were 11.4–14.7% within the first 20 m of the edge, dropping to 5.6 and 4.4% at 21–30 m and 31–40 m from the clearcut boundary, respectively.

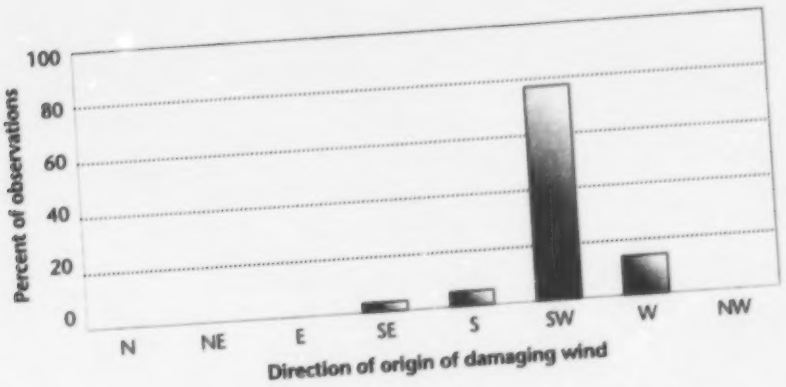

FIGURE 26 *Orientation of wind-damaged trees in partial cut treatments.*

Wind damage incidence along the outer windward perimeters of the clearcut (11–15%) is therefore of similar or greater magnitude to that encountered in some of the partial cut treatments.

Wind damage in the partial cuts Wind damage in partial cuts during these 1996 high-wind events was a mix of windsnap (43% of wind damage) and uprooting (57% of wind damage). Based on field observations in June, August, and September 1996, it appears that windsnap tended to occur more often during winter storms (probably due to the influence of deep snowpacks on the ground and heavy snowloads on tree crowns), while uprooting occurred more often in summer storms (as evidenced by higher levels of uprooting following the 30 August 1996 wind event compared to overwinter wind damage). Soils are not frozen in the winter at this and many other ESSF sites. Particularly in subalpine fir, windsnap is exacerbated by the presence of weak points in the stem, such as old forks from previous stem breakage, old scars, and stem decays.

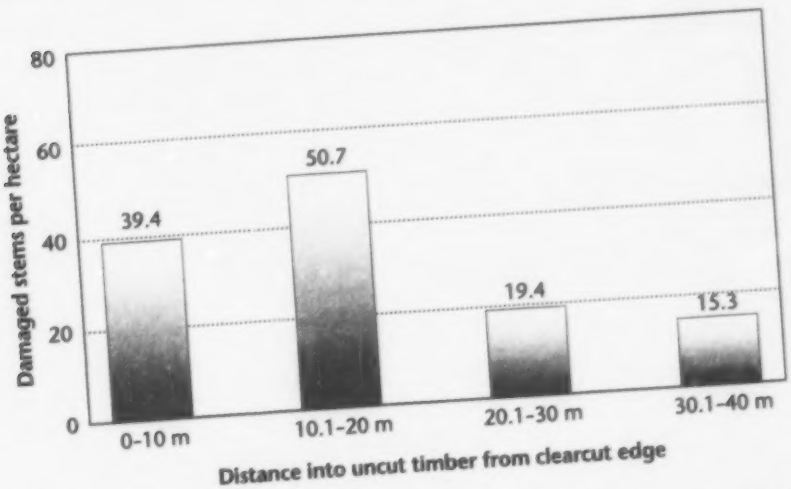

FIGURE 27 *Wind damage in relation to distance from edge along west- to south-facing sides of clearcut, fall 1996.*

Wind damage losses were higher in the single-tree selection and irregular shelterwood treatments than in the group retention treatment (Table 12). This suggests that retention of trees in aggregated clumps in the group retention treatment may provide some degree of mutual shelter and damping of wind forces for individual trees in the clumps. It appears that the dispersed pattern of harvest and individual-tree retention in the single-tree selection and irregular shelterwood treatments tends to thin out trees within clumps and reduce opportunities for mutual sheltering and damping of individual tree swaying during high-wind events.

Wind damage to Engelmann spruce and subalpine fir occurred in proportion to their occurrence in the stand, but some size classes of trees were subject to more damage than others. In the irregular shelterwood and single-tree selection treatments, wind damage occurred disproportionately in intermediate diameter classes (22.5–37.5 cm dbh) (Figure 28). Diameter classes <17.5 cm dbh appear to have low probability of wind damage in these treatments, probably due to sheltering by overstorey trees. Large codominant and dominant trees >40 cm dbh appear to have low to moderate probability of wind damage, perhaps due to their previous history of long-term wind exposure and acclimatization in the upper canopy.

Both field observations and plot data suggest that the heaviest damage from the August 1996 windstorm was relatively localized. We hypothesize that small-scale weather phenomena, such as high-speed convective downbursts embedded within the storm, may have been responsible for a portion of the overall damage.

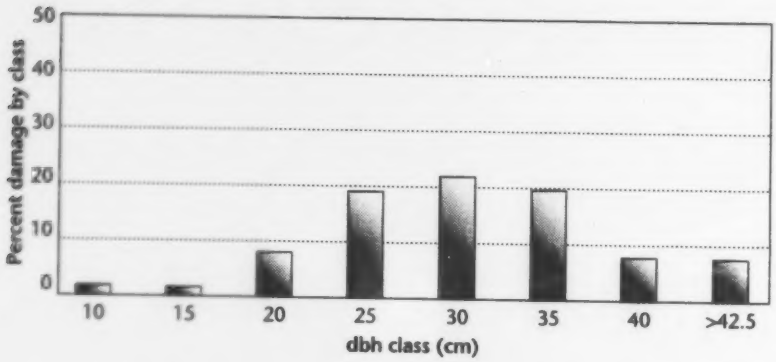

FIGURE 28 *Percent wind damage by dbh class in the irregular shelterwood and single-tree selection harvest treatments.*

6.7 Arboreal Lichens

SUSAN STEVENSON

Key Results

- Timber harvesting reduced available forage lichen to about one-third of its pre-harvest level, even though only half the live tree basal area was removed. Snags felled for worker safety accounted for most of the difference.
- There has been some redistribution of the lichens on the residual trees since harvesting, but heavy wind-scouring of lichens in the lower canopy was not observed.
- Growth rates of *Alectoria sarmentosa* appeared to be adversely affected by partial cutting, but *Bryoria* spp. seemed to tolerate at least moderately increased exposure. The clumped trees of the group retention area appeared to offer better conditions for the growth of *Bryoria* spp. than the more uniformly spaced trees of the irregular shelterwood.
- Trends in growth rates and genus composition suggest that the amount of *A. sarmentosa* in the lower canopy is declining in relation to the amount of *Bryoria*. This shift in composition is not expected to reduce habitat suitability for caribou.
- The amount of forage lichen currently available in the partial cuts is likely below the threshold of suitability to caribou.

6.7.1 **Objective** The objective is to determine the effects of partial cutting on the abundance and growth rates of arboreal forage lichens (*Alectoria sarmentosa* and *Bryoria* spp.) in the lower canopy of residual trees, where they are within reach of caribou.

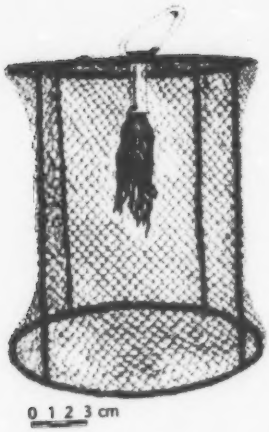

FIGURE 29 *Mesh enclosure used for study of lichen growth rates.*

6.7.2 **Methods** In summer 1989, pre-harvest lichen abundance was estimated using the clump method (Stevenson and Enns 1993) in thirty 0.01-ha plots each in the irregular shelterwood, single-tree selection, and unharvested control (UN) treatment areas. A 5-g clump of lichen was used as a standard unit and the number of clumps on each sample tree below 4.25 m was estimated. In 1992, the clump method and a new photo-based method (Armleder et al. 1992) were used to assess the abundance of *A. sarmentosa* and *Bryoria* spp. after harvest. In the photo-based method, each tree was classified into one of eight lichen abundance classes (0, 1, 2, 3, 3.5, 4, 4.5, or 5; in which 0 indicates no lichens and 5 indicates very high lichen abundance). The assessments were repeated in 1996 and 2000, using only the photo-based method. Beginning in 1992, the percentage of the forage lichen in the lower canopy of each tree composed of *A. sarmentosa* was also estimated; the remainder was *Bryoria* spp. All assessments were done by the same observer. Details were reported by Stevenson (1997).

Growth rates of arboreal lichens were measured by repeatedly weighing lichen thalli that were attached to an artificial substrate and grown in the field. The lichens were glued with silicone seal onto glass tubes, which were fitted into mesh enclosures (Figure 29) and suspended from the branches of trees 3–4 m above the ground. Twenty samples each of *A. sarmentosa* and *Bryoria* spp. were placed in the irregular shelterwood, the group retention, and the unharvested control area. In spring and fall, the lichens were brought to a laboratory in which temperature and humidity were controlled, allowed

to stabilize, reweighed, and returned to the field. A publication on lichen growth rates at Lucille Mountain, which includes a detailed description of the methods, is in preparation (Stevenson, in prep.).

Analysis of variance was used to compare continuous variables, and Pearson chi-square tests were used to compare frequency distributions. The level of significance for all tests was $p<0.05$. Standard errors shown in Figure 30 were calculated separately for each mean.

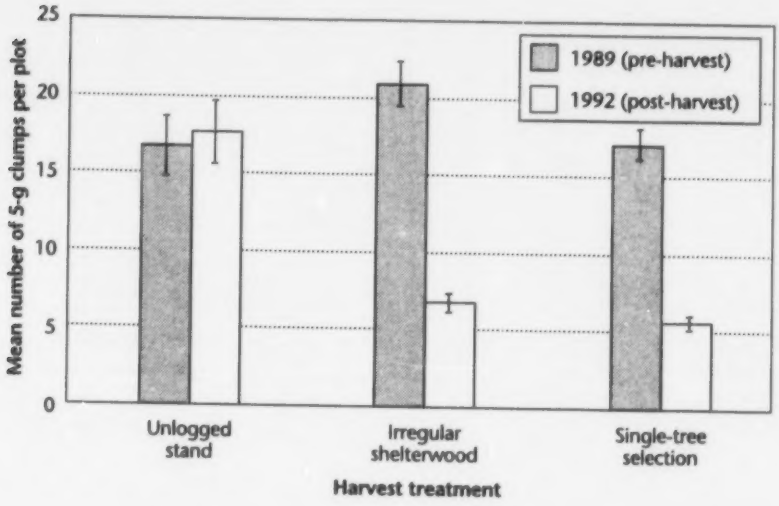

FIGURE 30 *Arboreal lichen forage available to caribou in sample plots before and after partial cutting.*

6.7.3 Results

Pre-treatment vs. first post-treatment abundance assessments Lichen abundance in plots was similar before harvesting in all three treatment areas; after harvesting it was much reduced in the two partially cut areas (Figure 30). The difference between the percentage of lichen removed by the harvest (67%) and the percentage of live tree basal area removed (49–50%) was due largely to the loss of lichens on the snags that were felled for worker safety. Figure 30 does not include the additional loss of lichens from roads and landings.

Little lichen was lost from the trees that were still standing after harvesting. Mean differences between lichen estimates on residual trees before and after the harvest were small and did not differ significantly among treatments.

Post-treatment assessments Changes in lichen abundance on individual trees, without regard to stem density, were assessed by comparing the frequency distributions of the lichen abundance classes. The frequency distributions of the lichen abundance classes in the unlogged area (Figure 31) did not differ significantly among years, but the frequency distributions in the partially cut area (Figure 32) did. The number of trees in the partial cut rated as having very low lichen abundance (0 or 1) declined with time (Figure 32), but there is no obvious pattern in the other lichen abundance classes.

Frequency distribution of the percent *Alectoria* classes differed among years in both the unlogged and the partially cut areas. The fluctuations in the unlogged area (Figure 33) do not suggest any clear pattern. In the partial cut (Figure 34), the number of trees in the lowest percent *Alectoria* class increased with time, while the number of trees in all the other classes decreased.

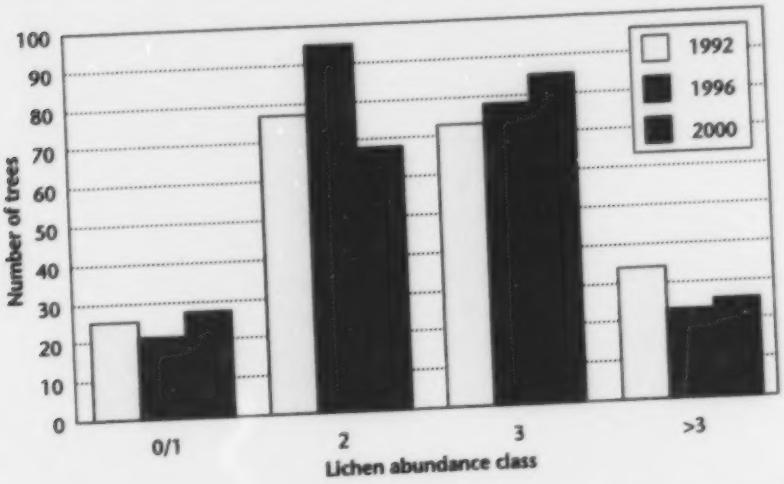

FIGURE 31 *Frequency distribution of lichen abundance classes of sample trees in the unlogged stand, 1992, 1996, and 2000.*

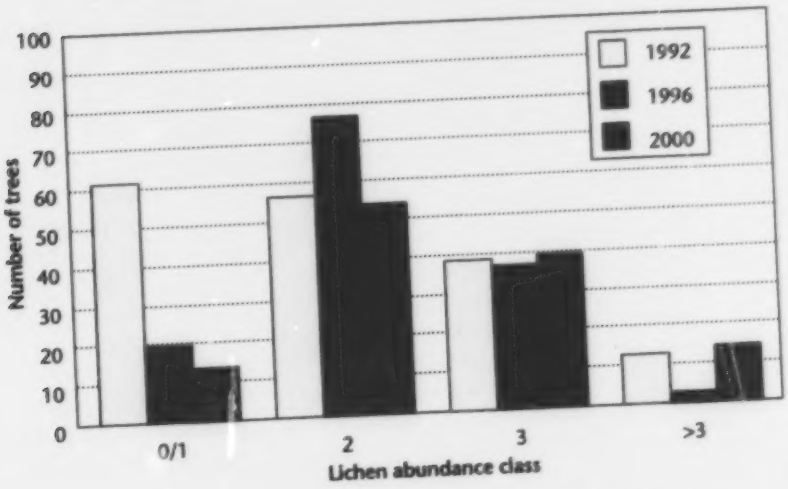

FIGURE 32 *Frequency distribution of lichen abundance classes of sample trees in partially cut areas (irregular shelterwood and single-tree selection), 1992, 1996, and 2000.*

Lichen growth rates Although pre-treatment growth rate data were collected, the methods were still being developed at that time and the data are not reliable. Collection of reliable data began in June 1993 and continued through September 2000; analysis is in progress. During the 64-month period from June 1993 to October 1998, the samples of the light green lichen *Alectoria sarmentosa* gained an average of 135% of their initial mass, and the samples of the dark brown genus *Bryoria* spp. gained an average of 170% of

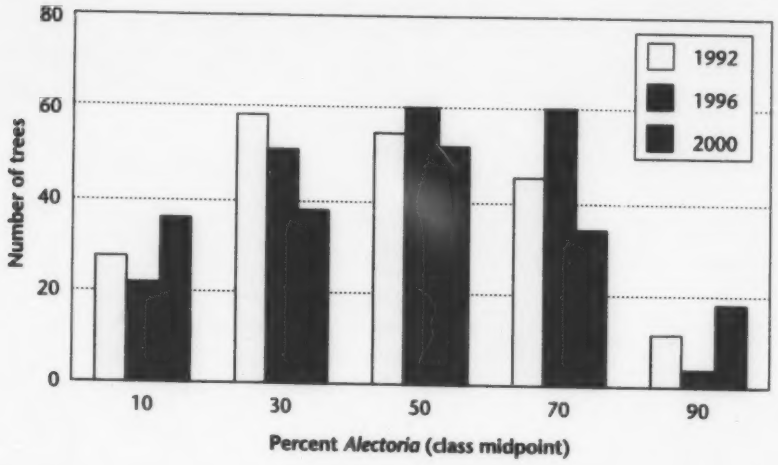

FIGURE 33 *Frequency distribution of percent* Alectoria *classes of sample trees in the unlogged stand, 1992, 1996, and 2000. Classes represent the percentage of the total amount of forage lichen below 4.5 m that was* Alectoria*; the remainder was* Bryoria.

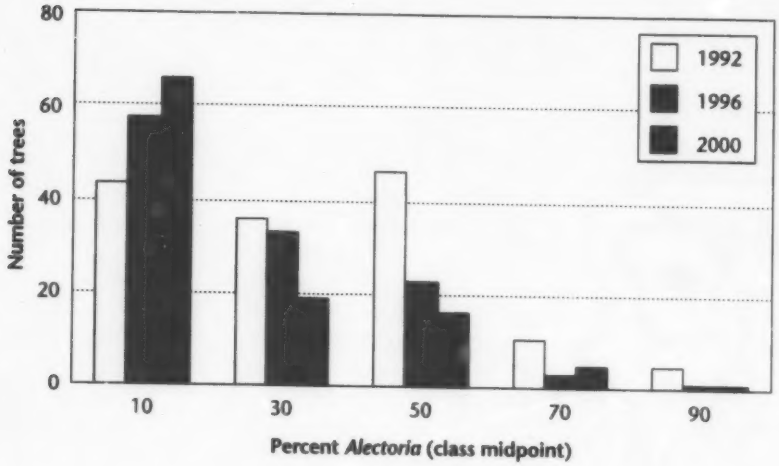

FIGURE 34 *Frequency distribution of percent* Alectoria *classes of sample trees in the partially cut area (irregular shelterwood and single-tree selection), 1992, 1996, and 2000. Classes represent the percentage of the total amount of forage lichen below 4.5 m that was* Alectoria*; the remainder was* Bryoria.

their initial mass. This change in biomass is a function of both net carbon gain (growth) and biomass loss through fragmentation.

Overall, *Alectoria sarmentosa* grew significantly more slowly in the partial cut treatments than in the unharvested control area. *Bryoria* grew significantly faster in the clumped trees of the group retention area than in the more uniformly spaced trees of the irregular shelterwood area; growth rates in the group retention area appeared similar to those in the unharvested control (Stevenson, in prep.).

Comparison of summer growth rates with climate data suggests a positive relationship between lichen growth and rainfall (Stevenson, in prep.). There was no apparent association between lichen growth during summer and temperature, or the percentage of potential solar radiation.

6.7.4 Discussion When a stand is partially cut, there is an initial reduction of lichen abundance that is at least proportional to the amount of timber removed. Subsequently, there may be changes in both the growth rates and the fragmentation rates of the lichens that remain.

Because caribou require large areas of unfragmented habitat, the recommended management goal for mountain caribou winter range is to maintain it in a condition that is suitable for caribou use at all times (Stevenson et al. 1994; Stevenson et al. 2001). Although minimum levels of lichen abundance required to support caribou have not been established, harvesting practices that result in the loss of more that two-thirds of the original amount of forage lichen seem unlikely to adequately maintain caribou habitat. Based on results from Lucille Mountain and other sites with different partial cut prescriptions, biologists have recommended a maximum volume removal of 30% for partial cuts in caribou winter range (Stevenson et al. 1994; Stevenson et al. 2001). Although the level of timber removal at Lucille Mountain was higher than currently recommended levels, the trial is providing valuable information, because it allows for investigation of the response of the lichens to an extreme treatment.

At some sites with high volume removal, there has been considerable loss of lichen from the residual stand due to wind-scouring of the newly exposed trees (Stevenson et al. 2001). At Lucille Mountain, the data do not suggest that an overall loss of lichen has occurred in the lower canopy of the residual trees. However, the increased number of Class 2 trees and decreased number of trees greater than Class 3 observed in 1996 in the partial cut and, to a lesser extent, in the unlogged area, may have resulted from high winds in winter 1995–1996 (Section 6.6).

The growth rate studies have shown that the two genera of arboreal lichens respond differently to the changed canopy environment in the partially cut area. Whereas *A. sarmentosa* appears to be adversely affected by increased exposure, *Bryoria* spp. were adversely affected only in the more uniformly spaced trees of the irregular shelterwood. This difference in growth rates helps to explain the shift in genus composition that appears to be taking place in the partial cut (Figure 34). The change in genus composition will probably not have any adverse effects on caribou, as they prefer *Bryoria* spp. to *A. sarmentosa* when they are on high-elevation, late-winter ranges (Rominger et al. 1996).

The abundance and genus composition of the lichens observed at Lucille Mountain were consistent with results obtained in the southern Selkirks, where Rominger et al. (1994) and Miller et al. (1999) found that individual trees in partial cuts had amounts of arboreal lichen similar to or higher than

trees in unlogged stands, but a higher proportion of *Bryoria*. Results of growth-rate studies at Lucille Mountain were similar to those obtained at Pinkerton Mountain in the ESSFwc subzone, where *A. sarmentosa* grew more slowly in a single-tree selection block with 30% volume removal than in the unlogged control area; growth rates of *Bryoria* spp. did not differ (Stevenson et al. 2001). In the Quesnel Highland, however, growth rates of *Bryoria* spp. were lower in group selection treatment units than in the unlogged control area (Stevenson et al. 2001). It is unclear why the results of these studies differed. It does seem clear, however, that *A. sarmentosa* is adversely affected by any opening of the forest canopy, whereas *Bryoria* spp. tolerate much higher levels of exposure.

6.8 Rates of Litter Decomposition

CINDY PRESCOTT

Key Results

- Decomposition rates of pine needle litter, aspen leaf litter, and forest floor material in each of the silvicultural treatments were similar to those in the uncut forest.

6.8.1 Objective One of the ecological processes critical to the functioning of forest ecosystems is the decomposition of organic matter. Through the related processes of decomposition and mineralization, litter is broken down, and the carbon and nutrients within the litter are released into the forest floor, where the nutrients are available for plant uptake. The rate of decomposition depends on the level of microbial activity, which is largely determined by the prevailing climate (temperature and moisture). It is generally thought that decomposition is faster in clearcuts than in forests due to greater microbial activity resulting from the warmer, moister conditions in clearcuts. However, studies have shown that decomposition rates may actually be faster, slower, or the same in clearcuts compared with forests, depending on the regional climate (Yin et al. 1989). Even less is known about the effects of alternative silvicultural systems, such as partial cutting or patch cutting, on decomposition rates. In an oak forest, Yin et al. (1989) found rates of decomposition in a shelterwood (15 years after harvest) to be more similar to those in an uncut forest than in a clearcut (5 years after harvest). Thinning forests has been shown to increase (Piene and Van Cleve 1978), decrease (Weetman 1965), or have no effect (Will et al. 1983) on decomposition rates. The Lucille Mountain study provided an opportunity to test the influence of alternative silvicultural systems on rates of decomposition.

6.8.2 Methods Three litter types were selected to represent a range of substrate types: lodgepole pine needle litter, trembling aspen leaf litter, and forest floor material. The pine and aspen litter was collected in the Kananaskis Valley of Alberta and the forest floor material was collected from a mixed conifer forest in the University of British Columbia Research Forest near Vancouver, B.C. These three standard substrates were used in a suite of decomposition experiments in British Columbia.

Decomposition rates were measured as mass loss during field incubations of litter in enclosed mesh bags. Litterbags were constructed of fibreglass screening and were usually 10 × 10 cm, with 1.5-mm pores (0.5 mm for forest

floor). Two grams of dried litter or forest floor were inserted into the bags, and the open end was stapled shut. Bags of lodgepole pine needles and forest floor were installed in one plot of each treatment (clearcut, irregular shelterwood, summer patch cut, and old growth) in August 1993; bags of trembling aspen leaves were installed in August 1994. Bags containing foliar litter were pinned to the surface of the forest floor; bags containing forest floor material were buried in the forest floor. At annual intervals for 5 (pine), 4 (forest floor), and 3 (aspen) years, seven bags of each type were collected

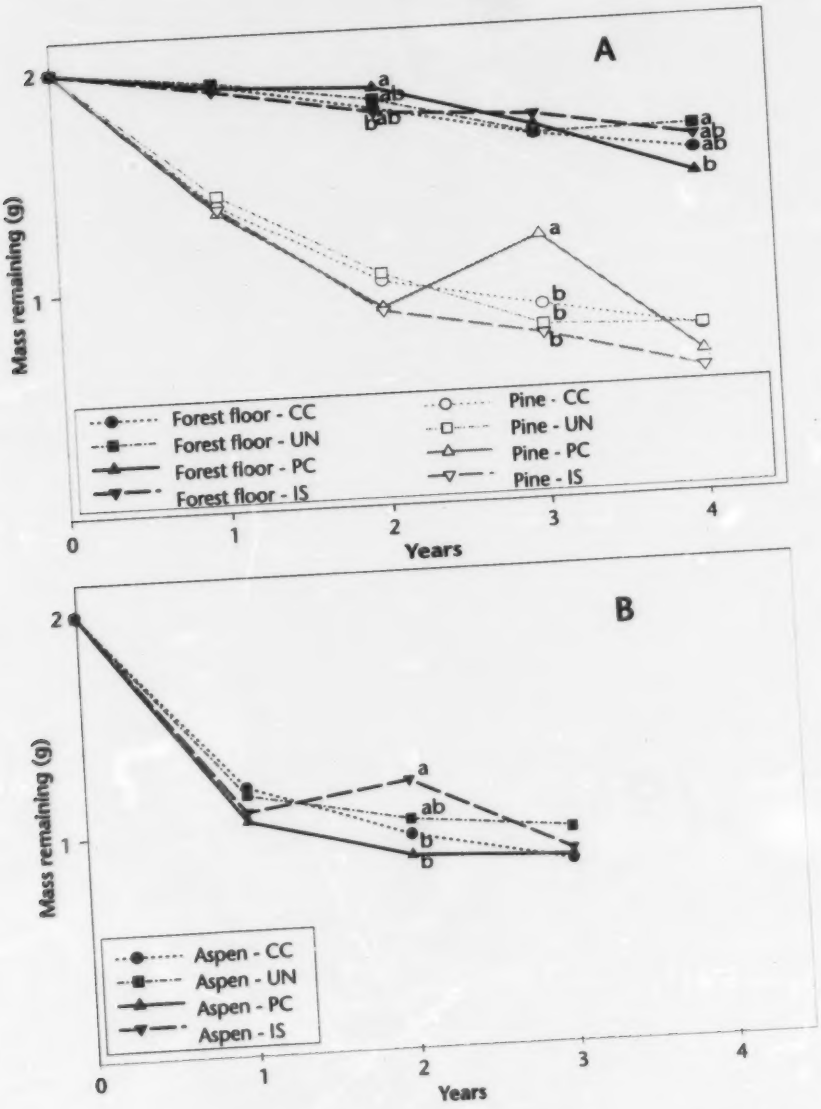

FIGURE 35 *Mass of lodgepole pine needles (A), forest floor (A), and trembling aspen leaves (B), remaining after decomposition for 3 or 4 years in clearcut (CC), unlogged (UN), patch cut (PC), and irregular shelterwood (IS) plots. Significant differences between treatments are indicated by different letters.*

from each plot. The contents of each bag were dried at 65° C, and the weight of litter remaining was measured.

6.8.3 **Results** Rates of mass loss of the three litter types in the four treatments are shown in Figure 35. Statistical evaluation of treatment differences was questionable due to the lack of replication, but results of one-way ANOVA and Tukey's multiple range test are presented, for which the seven bags per plot were treated as replicates. Although there were occasional differences in mass remaining among the treatments, no consistent pattern emerged for any litter type.

6.8.4 **Conclusion** There was no indication that clearcutting or any of the other types of openings at Lucille Mountain affected the rate of litter decomposition. This is similar to findings in an ESSF forest at the Sicamous Creek trial and in several other forest types in British Columbia (Prescott et al. 2000). Overall, these results indicate that we should not expect faster decomposition in clearcuts than in forests in British Columbia.

7 IMPLICATIONS FOR MANAGEMENT AND RESEARCH

The core objective of the Lucille Mountain Project is to improve our understanding of climatic and ecological processes affecting the development of conifer regeneration in ESSF forests, and how these are modified by different silvicultural treatments and residual stand structures. The trial was motivated by the need to find a better balance between apparently conflicting forest management objectives. It was designed to explore a number of related silvicultural and ecological questions and "working hypotheses." The initial results provide us with intriguing new evidence to examine old assumptions about the nature of subalpine climate, ESSF regeneration processes, and possibilities for stand structural manipulation.

In addition to original studies on regeneration issues, the stands created in this trial also provide opportunities to investigate a range of questions related to management of residual ESSF stands following different types and patterns of forest harvesting. These questions have included both potential benefits of stand structural retention, such as maintenance of arboreal forage lichens in partial-cuts, and risks, such as wind damage to trees within treatments or along treatment edges.

This section synthesizes the findings to date of individual studies at Lucille Mountain. It is intended to provide insight into the overall effects of different management practices on ecosystem function and regeneration processes in this subalpine forest. In addition, we consider to what degree the results and insights achieved by this study can be extrapolated to other ESSF sites. Finally, we discuss potential research questions and further work necessary to validate the initial findings of this trial.

7.1 Stand Structural Effects of Harvest Treatments

Different silvicultural systems partition the resources of the site differently among the various components of the vegetation. Through their influence on microclimate, different residual stand structures affect a variety of stand attributes, such as establishment and growth of young trees and development of the understorey vegetation. The effects of the residual stand on growth of young trees may be especially marked at high elevations, where productivity is low and light and temperature can both be limiting to tree growth. As well, silvicultural systems differ in the amounts and distribution of structures on which some components of the vegetation depend, such as cone-bearing trees and old woody substrate on which arboreal lichens can grow. This section summarizes the key differences in stand structure resulting from the harvest treatments at Lucille Mountain.

Clearcutting at Lucille Mountain resulted in the loss of all standing trees and the structures associated with them, as well as most of the advanced regeneration. Site resources are now shared between the understorey vegetation and planted regeneration. Initially, soil disturbance during summer harvesting reduced vegetation cover, giving the planted regeneration an early competitive advantage. This initial reduction was followed by an influx of early successional herbs, and subsequent recovery of the shrub layer.

In the partial cuts, the resources of the site are shared among the trees in the residual stand, the new regeneration, and the understorey. Some older trees, along with their structural attributes, are retained throughout the stand at all times. Most trees that were dead at the time of harvest were felled, in compliance with Workers' Compensation Board regulations, but some new snags have been created by wind and other damage agents. Established immature trees were protected where possible during logging to become future crop trees. Because all partial cuts were logged in winter, disturbance of the soil and the understorey vegetation was lower than in summer-logged treatments.

Post-harvest growth of the residual stand, as measured by basal area increment, has been similar in all three partial cut treatments. There was a strong positive relationship between the basal area of the stand immediately after the harvest, and the basal area increment per hectare during the next 7 years. As well, there was a positive correlation between initial tree diameter and post-harvest basal area increment for individual trees, suggesting that large-diameter trees were in a superior competitive position in relation to smaller trees. Growth of planted regeneration was limited by the residual stand, primarily through its effects on light and soil temperature.

The 0.2-ha patch cut treatment is intermediate between the clearcut and the partial cut treatments, in that the overstorey is completely removed from the openings, but the openings are small enough to be influenced by the surrounding mature forest. Above- and belowground gradations of temperature and other environmental variables result. Over time, these gradations may result in greater structural diversity within patch cuts than within the clearcut.

Of the non-timber resource values that are potentially maintained through non-clearcutting silvicultural systems, only arboreal lichens were studied at Lucille Mountain. Although about one-half the pre-harvest basal area was removed, less than one-third of the original amount of forage lichen was available after harvesting. Based on results at Lucille Mountain and other silvicultural systems trials, biologists have recommended a maximum volume removal of 30% for partial cuts in caribou winter range.

Wind damage losses were lower in the group selection units than in either the single-tree selection or the irregular shelterwood units. We speculate that retention of trees in clumps may shelter the leeward trees, and dampen the swaying of individual trees in the clump. Because of the low losses to wind, the group selection treatment unit was the only one of the three partial cut units in which gross growth exceeded mortality during the 7 years after logging. However, because of the small size of the treatment units, these results should be tested more extensively.

Retention of trees in clumps also appeared to have advantages for arboreal lichens. Growth rates of *Bryoria* spp., the favoured late-winter forage lichen for mountain caribou, were as high in the group selection unit as in the uncut mature timber. In the more uniformly spaced trees of the irregular shelterwood, growth rates were significantly lower.

7.2 ESSF Regeneration Processes

Three approaches to regenerating spruce and subalpine fir in ESSF forests were examined at Lucille Mountain. These included the establishment of new seedlings by natural regeneration or planting, and retention of established advance regeneration and larger leave-trees from the residual stand.

Natural regeneration in the ESSF forests at Lucille Mountain is primarily constrained by the availability of suitable seedbeds (mineral soil, mixed mineral-organics, and rotting wood) for germination and establishment, and by the supply of viable seed. Both seedbed availability and seed supply are important limiting factors for successful natural regeneration in ESSF forests. Where seedbeds are adequate, seed supply becomes the main limiting factor to natural regeneration in these subalpine forests, and vice versa.

Following silvicultural treatments in ESSF forests, availability of suitable mineral soil or mixed mineral-organic seedbeds depends on the type and intensity of disturbance to the forest floor, and the time since disturbance. Good cone crops are infrequent and episodic due to climatic limitations on conifer cone and seed production. In many years, poor cone crops are typical, and seed and cone insects diminish the already limited seed supply (Eastham and Jull 1999). When good cone crops do occur, there tends to be good seed availability in dispersed partial cut and small patch cut treatments. In these treatments, subalpine fir seed is much more abundant than spruce seed, due to the much higher abundance of cone-bearing subalpine fir in the stand relative to Engelmann spruce. Future assessments at Lucille Mountain will provide a longer-term indication of how long the seedbeds created by harvest treatments remain receptive to establishment of natural regeneration. Greene et al. (1999) argue that for boreal (and analogous subalpine) forest types, there is generally a narrow window of opportunity for invasion of disturbed areas by trees; by about the fifth to seventh year following disturbance, the accrual of litter, mosses, and vegetation re-occupy most seedbeds and make further conifer establishment a rare event.

Large clearcuts reduce natural regeneration opportunities for both spruce and subalpine fir, because much of the harvested area is far from available seed sources along uncut stand edges. Seed of these species is limited in its ability to disperse by wind from seed-bearing trees. A review of other studies in spruce–subalpine fir forest types suggests that, typically, seedfall in clearcuts decreases more or less exponentially with increasing distance from the adjacent uncut stand edges (Coates et al. 1994). The rate of decrease is higher for the more heavy-seeded subalpine fir than the lighter-seeded Engelmann spruce.

The research trials at Lucille Mountain have demonstrated that environmental conditions in the clearcut treatment are indeed suitable for natural regeneration, given an adequate supply of seed and seedbeds. In the clearcut treatment, the summer harvesting tended to create well-distributed seedbeds via forest floor disturbance and mineral soil exposure. Due to thin forest floors on many ESSF sites, even modest treatment impacts may create adequate seedbeds. Seed availability was the main limiting factor to achievement of natural regeneration in this treatment, because most of the 32-ha clearcut was a considerable distance (>100 m) from upwind seed sources.

Potentially, forest managers can increase natural regeneration opportunities in high-elevation ESSF forests by pursuing several silvicultural strategies, sometimes simultaneously. Suggested strategies include:

- modifying harvest patterns, cutblock boundary orientation, and width of harvest openings to retain seed sources closer to the entire harvest area; and
- ensuring adequate seedbeds (mineral soil or forest floor disturbance) through application of suitable harvest and/or site preparation methods.

Ideally, these need to be carried out in years with adequate cone crops, but, regardless, natural regeneration ingress following such treatments is an inherently slow process in subalpine forests, requiring a decade or more (Fieldler et al. 1985). Frequently, achievement of adequate regeneration stocking to legislated standards may require augmentation or fill-planting with planted seedlings.

These recommendations are consistent with a comprehensive review of regeneration dynamics of "boreal" tree species (Greene et al. 1999). These authors noted that natural regeneration has been criticized due to its unreliability relative to planting. This problem is especially acute for white spruce (and the closely related Engelmann spruce), species that have seed production, seed supply, and dispersal characteristics that inhibit the reliable stocking of large clearcuts. Greene et al. (1999) identified three key principles that can reduce, but not eliminate, limitations to natural spruce regeneration in the design of silvicultural systems. We note that these principles appear to apply equally to fostering natural regeneration of subalpine fir. The key principles of Greene et al. (1999) are:

- Reduce the maximum distance from seed source to seedbed.
- Enhance the density of seed deposition by leaving a large number of source trees at cutblock edges (and maximizing edge through irregular cutblock boundaries).
- Expose as much mineral soil as possible.

Greene et al. (1999) cautioned that, for spruce, "the prescription outlined above would at best allow foresters to obtain adequate stocking the majority of the time, but spot planting would undoubtedly be required in the majority of cases if we are bound to meet what is perhaps an unnatural stocking criterion."

Planting of spruce and subalpine fir reduces the uncertainty associated with natural regeneration processes and the supply and viability of natural seed. However, the prospects for long-term survival and growth of established conifer regeneration, either natural or planted, depend on establishment in a

favourable location or microsite. Historically, there has been uncertainty among silviculturists about the advantages and disadvantages of retaining residual trees after harvest relative to protection and enhancement of established conifer regeneration in subalpine ESSF forests. The results to date from this trial shed some light on this debate.

Overstorey shelter affected the incidence of visible injury to newly planted Engelmann spruce seedlings following two consecutive growing-season frosts in August 1992 at Lucille Mountain. Spruce seedlings in the clearcut had significantly higher incidence of damage than those in more sheltered treatments. Despite the severity of the frost in the clearcut treatment, most injury was non-lethal, resulting in necrotic buds, leaders, and lateral foliage, but little immediate mortality. However, it appears that frost injury has a longer-term effect on newly planted seedlings. Seven years later, seedlings visibly injured by frost in 1992 had a significantly higher mortality rate than seedlings without symptoms of injury. The frost damage itself was probably not directly responsible for increased seedling mortality rates. Field observations suggested that badly frosted seedlings had impaired recovery, stem form, and growth, placing them at greater risk of mortality from other factors, such as vegetation competition. On sites where growing-season frosts occur more frequently than at Lucille Mountain, cumulative impacts of repeated frost injury on seedling survival could be serious. Therefore, in frost-prone areas, partial cutting to maintain a residual overstorey (including harvesting in small groups) is a promising strategy for reducing frost risk to planted seedlings.

At Lucille Mountain, the most important ecological impact of the different silvicultural treatments on long-term seedling survival and vigour appears to be the effect of residual stand structures on the pattern and amount of incoming solar radiation (light and heat) reaching the seedlings. Interception of incoming solar radiation by residual overstorey canopies or adjacent stand edges negatively affected regeneration performance both directly (through available light levels) and indirectly (through changes in soil temperature). This effect was greater in treatments with a dispersed overstorey than in the 0.2-ha patch cuts. In addition to treatment-level differences, however, residual overstorey trees or uncut edges also exert local influences on performance of adjacent planted seedlings. At Lucille Mountain, both spruce and subalpine fir seedlings planted within 5 m of residual live trees had poorer growth performance than seedlings planted further away. Belowground interactions between regeneration and mature residual leave-trees are poorly understood, but have profound implications for silvicultural prescriptions and achievement of operational regeneration objectives in ESSF partial cuts.

In this trial, the relative effects of light availability and soil temperature on conifer growth were difficult to separate statistically, because the effects covary; increased light levels are associated with increased soil temperatures, and vice versa. This confounding of light and soil temperature effects is a fundamental problem in ecological research in this field, and difficult to unravel even with sophisticated investigative approaches.

Understorey vegetation in the vicinity of conifer regeneration affects seedling growth and vigour in two ways. First, vegetation may directly compete for above- and belowground resources with adjacent seedlings. Second, by shading of both the seedling and the surrounding ground surface, vegetation limits light availability and reduces adjacent soil temperatures in

the seedling root zone. The effect of the different treatments on potential vegetation competition also has to be considered dynamically. Some treatments, such as summer logging, clearcuts, and patch cuts, may initially reduce vegetation competition through physical impacts on shrubs. In the same treatments, however, forest floor disturbance, removal of the canopy, and changes in understorey species composition may combine to increase the vigour and cover of understorey vegetation complexes. This may ultimately have a long-term impact on regenerating trees.

Based both on this study and related ESSF regeneration studies elsewhere in British Columbia, it is apparent that there are direct interactions between treatment effects on light (incoming solar radiation) and soil temperature. Both factors appear to have a significant role in influencing regeneration performance, but the relative importance of each factor on long-term growth of regeneration in different ESSF silvicultural systems has yet to be adequately determined. In the partial cuts, where regeneration has been planted in an intimate mixture with overstorey leave-trees, regeneration outcomes may be even more complex. In these areas, it can be hypothesized that overstorey leave-trees may not only influence regeneration by passive effects on understorey light levels and soil temperature, but also by direct or active interactions (e.g., competition for soil resources) of live overstorey leave-trees with planted regeneration. This trial provides some empirical evidence for these potential competitive interactions between regeneration and leave-trees.

Observations of the 7-year post-harvest stand growth and development in the partial cut treatments at Lucille Mountain suggest that the potential for vigorous release and productive growth of larger advance regeneration and residual canopy trees in ESSF partial cuts have been substantially underrated in the past. The consistent post-treatment growth of both small and large residual trees observed in this trial suggests that forest managers may be well-justified in using partial cut silvicultural options for incorporating these residual tree layers into future ESSF stand management. These options will be particularly important for management objectives in which greater complexity of stand structure is considered important.

Based on results of both this trial and other ESSF trials in British Columbia to date (Huggard et al. 1999; Stevenson et al. 1999; Newsome et al. 2000), risk factors to advance regeneration and larger stems, such as windthrow, are less of a concern than previously anticipated, and, like logging damage risks, can be managed and reduced proactively by appropriate pre-harvest assessments, cutblock design, and harvest methods. The importance of active measures to protect advance regeneration from logging damage during harvesting is supported by numerous studies and literature reviews from the ESSF and other northern coniferous forest types (Herring 1977; Youngblood 1990; Greene et al. 1999).

7.3 Implications for ESSF Reforestation Practices

Clearcut harvesting has predominated in spruce–subalpine fir forests in British Columbia since the early 1970s. Therefore, reforestation standards (including conifer species selection and stocking tables) have been developed for the primary management objective of sawlog production under an even-aged system (B.C. Ministry of Forests 1995b, 2000). However, as the use of partial cut silvicultural systems is becoming more common in ESSF forests to meet many non-timber objectives, more suitable reforestation

objectives for these partial cut systems need to be developed. Current reforestation guidelines acknowledge this reality: "Where another management objective is more important than conifer sawlog production, and where following these guidelines would negatively affect that objective, deviating from the guidelines is recommended. Both species selection and stocking can be done outside the guidelines if appropriate. This may include fitting into higher level plans . . . or creating a stand structure for a value-added end product, biodiversity, or habitat objectives." (B.C. Ministry of Forests 2000).

Unlike clearcut systems, partial cut systems (including those with many small openings or retention patches) create or maintain complex stand structures with high vertical and horizontal heterogeneity. In partial cuts, regenerating seedlings tend to be influenced either directly (through competition for site resources) or indirectly (through modified growing environments) by the residual overstorey or surrounding stand edges. Unlike plantations in clearcuts, partial cut stands are managed both for leave-trees and for new regeneration. Most or all of these tree layers are potential crop trees. Clearly, under the silvicultural conditions found in ESSF partial cuts, conventional reforestation standards designed for even-aged plantation objectives reach the limits of their practical utility, and may exceed the range of ecological conditions for which they were designed. The effects of different silvicultural systems and complex stand structures in regeneration performance in the ESSF and other biogeoclimatic zones is an active area of research in British Columbia (Hollstedt and Vyse 1997; Newsome et al. 2000). The findings of the Lucille Mountain study and other research projects have implications for, and the potential to inform, future policy development regarding reforestation standards.

In 1987, changes to British Columbia's legislation assigned reforestation obligations to forest licensees, and codified provincial stocking standards and reforestation obligations. These legislative changes brought in the concept of "free-growing" seedlings as a standard for successfully established conifer stands free of vegetative competition. They defined maximum time limits following harvesting for establishment of conifer seedlings through planting (4 years) and natural regeneration (7 years), and defined minimum and maximum periods for the achievement of free-growing seedlings. These standards were adopted in the *Forest Practices Code of British Columbia Act* (1995), through the Establishment to Free-Growing Guidebook (B.C. Ministry of Forests 1995b, 2000). Based on this guidebook, post-harvest target stocking standards for regeneration on most sites in the ESSF zone (and many other interior biogeoclimatic zones) are 1200 well-spaced sph (defined as 2- to 2.5-m spacing), while the minimum stocking standard is 700 well-spaced sph.

Creating ecologically appropriate reforestation standards more applicable to the range of feasible silvicultural systems in the ESSF zone requires reliable long-term scientific information and operational experience. Historically, forest managers have had little quantitative information or trials by which to rigorously assess the expected relative performance of planted or natural regeneration in partial cuts and clearcuts. Regeneration studies at the Lucille Mountain trial, and complementary ESSF silvicultural systems trials throughout the east- and south-central interior of British Columbia, will provide the long-term scientific baseline data that will help inform site-specific modifications to ESSF reforestation standards in a variety of stand structures.

Key findings of regeneration research at Lucille Mountain applicable to reconsideration of ESSF reforestation standards are as follows:

- Given the proper conditions, natural, advance, and planted regeneration strategies all contribute to the regeneration of subalpine fir and spruce on harvested ESSF sites.
- Although seed crops in the ESSF are inherently highly variable, natural regeneration opportunities can be significantly enhanced if silvicultural systems are designed to do so. Critical for enhancing natural regeneration are treatments that will produce suitable seedbeds (i.e., mineral soil or mixed mineral-organic) and cut-and-leave patterns that optimize opportunities for seed dispersal of spruce and subalpine fir (smaller and narrower openings or dispersed partial cuts).
- Residual stand structure in the ESSF (including dispersed leave-trees and edges of small patch cuts) has measurable benefits in minimizing or mitigating impacts of severe frosts on regeneration, contributing to available natural seed supply and natural regeneration, and post-harvest wood production. Risks to residual stems, including windthrow or logging damage, should always be a concern in management, but may be mitigated proactively through prescription of appropriate harvest removal levels, harvest patterns, and skid trail design.
- Conversely, planting seedlings too close (<5 m) to existing leave-trees or forest edges appears to reduce long-term survival and growth rates of those seedlings.
- Lucille Mountain research results suggest that planting is necessary to achieve legislated stocking standards within prescribed time periods in the ESSF. However, these results also support practices that augment stocking by promoting natural regeneration and retaining advance regeneration and larger residual stems.

Planting is the most expeditious and direct method for ensuring spruce composition in the regenerating stand under any silvicultural system, given the demanding seedbed requirements and usually scarce availability of viable natural spruce seed in ESSF forests (Section 6.3; Eastham and Jull 1999). Planting of subalpine fir may also be necessary in large clearcuts or close equivalents where distance to upwind seed sources is greater than 100 m (three to four tree heights), but less necessary in partial cuts or small openings where seed sources are available. However, natural and advance regeneration should not be discounted in the ESSF, because their contributions to stocking can significantly modify both species composition and spatial stand structure in the regenerating stand. This aspect of stand regeneration is becoming more important in northern and ESSF forests, as the focus of regeneration silviculture and stand management evolves towards producing more diverse mixed-species and complex stands with irregular vertical and horizontal structures (Kohm and Franklin 1997; Greene et al. 1999; Stevenson et al. 2001).

On sites where severe summer frosts may occur, risk of frost damage to planted Engelmann spruce seedlings is substantially reduced by maintaining canopy cover of residual trees or planting in openings two tree heights or less in width. On this sloping research site at Lucille Mountain, growing-season frosts do not occur frequently, so protection of newly planted spruce seedlings from frost is not an urgent management concern here. However, on

other sites with very frequent growing-season frosts, the influence of a sheltering partial cut could potentially make the difference between successful regeneration establishment and repeated regeneration impairment or failure.

Results from the Lucille Mountain trial to date indicate that establishment of planted Engelmann spruce and subalpine fir has been most successful under conditions where spruce seedlings were placed in sufficiently open conditions, with adequate light availability and soil temperature, and minimal root competition with established leave-trees. All other factors being equal, seedling growth on ESSF sites tends to be favoured by planting locations >5 m from residual leave-trees or mature stand edges. Because residual trees in partial cuts are often potential "crop trees" and occupy growing space in the stand, their presence tends to reduce the number of planting spots suitable for long-term establishment and growth. For reforestation prescriptions in ESSF partial cuts, forest managers need to consider overall management objectives, the spatial pattern and density of the residual stand structure, and the proximity of planted regeneration to leave-trees. These considerations will be relevant to the development of operational plans such as Silvicultural Prescriptions, Silvicultural Prescription regeneration objectives, and implementation measures, including microsite selection guidelines for tree planters. In many cases, it is likely that these considerations will result in modification of target planting densities, inter-tree spacing criteria, and regeneration stocking standards relative to those traditionally prescribed for clearcut systems.

On ESSF sites, prescriptions for non-clearcut silvicultural systems need to consider the future growing conditions and treatments necessary to ensure long-term survival and growth of spruce and subalpine fir. This is especially true where spruce is growing under the canopy of residual trees. Because larger leave-trees in a partially cut stand compete effectively with regeneration for site resources for volume and height growth (i.e., they occupy "growing space" in the stand), growth expectations for understorey seedling layers should be reduced accordingly. Ideally, ESSF silvicultural treatments should create gaps or openings in the stand sufficient to allow future regeneration room to grow relatively unimpeded by adjacent surrounding crop trees; otherwise, significantly reduced growth of regeneration may result. For example, spruce planted in the 0.2-ha patch cuts at Lucille Mountain showed modest reductions in early growth compared to the clearcut treatment, but current seedling vigour in these treatments is generally very good. Spruce growth in these treatments will probably improve over time as the height of the regenerating trees in the patch cut increases, relative to the fairly static height of the surrounding mature stand. Survival and 7-year growth of subalpine fir in the 0.2-ha patch cuts were generally equivalent to performance under clearcut conditions. Subalpine fir was found to be less sensitive than spruce to the influence of residual leave-trees, although previous comments regarding management of spruce in partial cut silvicultural systems still apply in general to subalpine fir.

Lucille Mountain trial results support species selection guidelines for the ESSF that recommend both spruce and subalpine fir for reforestation on these sites. Seven years after harvesting, subalpine fir survival and growth in the clearcut was almost identical to that of Engelmann spruce. Planting, natural or advance regeneration, or a combination should all be considered for regenerating or recruiting subalpine fir on harvested sites in the ESSF, especially in smaller or narrower openings. Large clearcuts that have long

distances to a seed source (>100 m) are likely to require planting, because the heavy seed of subalpine fir generally does not easily reach the interior of large openings.

7.4 Applicability to Other ESSF Areas

The sloping terrain, climate, podzolic soils, parent materials, sub-mesic to mesic site type, and *Rhododendron-Menziesia* understorey shrub community found at the Lucille Mountain site are typical of many ESSF sites in east-central British Columbia. Although the mapped location of the Lucille Mountain site is in the ESSFmm (moist mild ESSF), it is at the extreme northern edge of this subzone, and appears to be geographically transitional to a wetter, cooler ESSFwk1/wc3 complex (B.C. Ministry of Forests 1996) occurring just a few kilometres to the north. The northerly aspect accentuates the cool moist character of the Lucille Mountain research site.

This characterization is supported by comparing broad climatic attributes from long-term monitoring at the Lucille Mountain ESSF trial to climate data collected from three replicated ESSF silvicultural system trials in the Quesnel Highland, in the wet cool ESSFwc3 biogeoclimatic variant some 150–200 km southwest of the Lucille site. For this comparison, we examined growing-season Growing Degree Days >5° C (GDDs) and growing-season precipitation for the period 1995–1998 (Stathers 2001). Due to differences in measurement periods, these comparisons are general in nature.

For the Lucille Mountain site, annual growing-season GDDs ranged from 496 to 743, with a mean of 562; Quesnel Highland GDDs ranged from 472 to 884, with a mean of 632. Likewise, annual growing-season precipitation (mm) at the Lucille Mountain site ranged from 159 to 360 mm, with a mean of 260 mm; growing-season precipitation at the Quesnel Highland ranged annually from 158 to 345 mm, with a mean of 243 mm. These data support the contention that local climate at the Lucille Mountain Project site is similar to local climates observed at other research sites in nominally wetter and cooler ESSF subzones.

Given similar forest cover and ecosystems, it is not surprising to find similar climates at these different ESSF sites. That similarities are evident, despite large site-to-site differences in elevation, latitude, aspect, and topographic position, suggests that the geographic and elevational distribution of wetter, cooler ESSF ecotypes may correspond to similar climatic and growing environments in these areas.

8 CONCLUSIONS

The silvicultural systems study at Lucille Mountain was initiated for two main reasons: concerns about prior regeneration failures in high-elevation clearcuts, and concerns about situations where clearcutting did not adequately maintain non-timber resource values. In the decade since studies began at Lucille Mountain, much has been learned about successfully establishing plantations in ESSF clearcuts, and concerns about regeneration failures have diminished. Concerns about non-timber resource values remain high. While establishment of even-aged plantations in the ESSF now seems feasible on most sites, even-aged management may not always be a desirable goal. Uneven-aged management can produce more complex stands

that resemble natural ESSF stands and may address such non-timber values as biodiversity, watershed resources, and visual quality.

The Lucille Mountain study provides information about ecosystem responses to a variety of silvicultural systems, and has implications for management of both timber and non-timber resources. However, to avoid extrapolating inappropriately to other situations, it is important to recognize the limitations of the results presented here. The unreplicated design limits our ability to generalize to other sites. As well, the study was conducted in the ESSFmm subzone, and some responses described here may differ in other subzones. The Lucille Mountain site experienced very few summer frosts, probably because its topographic position allows good cold air drainage; caution must be exercised in transferring some results reported here to sites with poorer cold air drainage, even within the same subzone. Also, some responses observed during the first 8 years after harvesting are likely to change as stand development progresses.

Because the planned duration of the Lucille Mountain Project is approximately 100 years or more, monitoring of Lucille Mountain research installations and the baseline climate station will continue, given adequate resources, into the foreseeable future. Critical components of this continued monitoring and research at Lucille Mountain include:

- continued long-term monitoring of climate;
- annual surveys (from walk-throughs to detailed assessments) in each treatment to identify episodic disturbances, events, and damage agents;
- periodic (5-year) assessments of regeneration trials and related monitoring plots; and
- reassessment of lichen growth rates after the regeneration has developed enough to affect the lower canopy environment.

Monitoring of treatment responses at the Lucille Mountain trial has identified several important lessons with relevance for both research and forest management:

1. The factors or optimum conditions that favour successful regeneration establishment (either natural or planted) do not necessarily correspond with the factors or conditions that favour longer-term conifer regeneration growth and vigour.
2. Short-term regeneration responses to treatment may not be indicative of longer-term responses to treatment.
3. For some response variables, unusual or episodic climatic events may have important influences on long-term treatment results. Such events include infrequent but severe growing-season frosts, and extreme high-wind events. Therefore, regular and ongoing monitoring is crucial.
4. Even 100-m differences in elevation in the ESSF can significantly affect growing-season climatic conditions, and, by inference, the responses of seedlings to silvicultural treatments.

The adaptive management approach demands that forest managers and researchers be willing to critically re-evaluate assumptions and working hypotheses regarding ESSF forests, such as those stated in Section 3. In many cases, the problem with using such assumptions as a basis for management is that these assumptions have been shown to be not completely false, but also

not completely true. Forest managers and researchers need to explicitly state the underlying assumptions of forest practices, and to qualify these assumptions by identifying the range of ecological conditions under which they are likely (or unlikely) to be valid. An example is the identification of frost-prone sites versus sites where frost is not likely to be limiting, such as the Lucille Mountain site.

Likewise, assumptions and conclusions about the silvicultural viability of different ESSF regeneration options and silvicultural systems increasingly need to be examined and tested across the range of site types in our diverse ESSF forests. As well, new trials are expanding from a focus on silvicultural issues to a broader range of resource values, including the effects of forest practices on ecosystem function and productivity, biodiversity at many levels, and wildlife habitat.

Many such questions can be addressed only through the development of inter-disciplinary research and management approaches, including operational-scale experiments, trials, and monitoring programs. Such trials need to be large enough to adequately reflect the physical scale at which many ecological and management processes function (e.g., watersheds, landscape units, or timber harvesting areas). For example, the 30-ha treatment units at the Sicamous Creek study area have allowed investigation of the effects of various harvest patterns on animals as large as pine marten and spruce grouse (Hollstedt and Vyse 1997). At Mount Tom, in the Quesnel Forest District, a 1000-ha area is currently being harvested using the group selection silvicultural system, allowing, for the first time, an assessment of the direct effects of this type of partial cutting on habitat use by mountain caribou (Stevenson et al. 2001).

Other trials are building on ideas that were initially suggested by results from Lucille Mountain. The clump/gap structure characteristic of the ESSF has been identified as an important area for research (Jull et al. 1998, p. 62). What are the successional dynamics of these clumps? Does the distribution of foliage in subalpine stands with this clumped structure represent full site occupancy? What is the functional importance of the clumped trees? Further investigations of their functional importance for arboreal lichens have continued at Pinkerton Mountain (Stevenson et al. 1999). Group selection treatments at Pinkerton Mountain, Mount Tom, and Bearpaw Ridge have been designed to retain intact clumps along edges of openings. Also at the Bearpaw Ridge site, northeast of Prince George, a single-tree selection trial is planned in which units ranging from individual trees to small clumps have been marked for removal (Jull et al. 2001).

The inherent value of the Lucille Mountain Project is the continued development and accumulation of critical long-term data sets on ESSF climate, regeneration processes, and stand development in this poorly understood forest type. Of particular interest in the long term will be the opportunity to examine different patterns and rates of forest ecosystem recovery from these contrasting silvicultural treatments. This and related trials in British Columbia will provide some of the fundamental scientific knowledge supporting long-term, ecologically based forest management practices in the ESSF zone.

APPENDIX 1 Soils

PAUL SANBORN

Soils at Lucille Mountain have formed on a blanket or veneer of gravelly, medium- to coarse-textured morainal deposits over bedrock. The surface soil has predominantly silty textures, with high hazard ratings for both surface soil erosion and soil compaction and puddling (B.C. Ministry of Forests 1995c). The non-calcareous metamorphic bedrock (phyllite or schist) contributes to the extremely acidic reaction of the entire soil profile.

Based on examination of roadcuts and other exposures, the Lucille Mountain pedon described by Arocena and Sanborn (1999) (Tables A1 and A2) is representative of the predominantly well-drained soils in the area. This pedon is classified as an Orthic Humo-Ferric Podzol, based on the accumulation of carbon and pyrophosphate-extractable iron and aluminum in the B horizon (Soil Classification Working Group 1998). At the regional level, Humo-Ferric Podzols are the dominant soil Great Group formed on morainal parent materials throughout the Cariboo Mountains and the western slopes of the Rocky Mountains (Agriculture Canada 1992).

Mineralogical composition of the clay fractions in this soil was examined by Arocena and Sanborn (1999). Mica and chlorite dominates the clays in all horizons, comprising 40–65% and 10–20%, respectively, of these fractions, presumably reflecting the influence of local bedrock on parent material mineralogy. In surface horizons, weathering has transformed only a small proportion (<20%) of these inherited clays to expanding-type minerals (smectite, vermiculite). These soils therefore tend to have limited shrink-swell activity in response to wetting-drying cycles, potentially slowing rates of recovery from soil compaction.

The highest concentrations of nitrogen, sulphur, and available phosphorus all occur in the forest floor, underscoring the nutritional importance of conserving this material during harvesting and site preparation. Forest floor conservation is particularly important, given the very low sulphur concentrations in the mineral soil. The levels observed in this pedon were similar to those at other central interior sites examined by Arocena and Sanborn (1999), and are consistent with a broader pattern of sulphur deficiency in British Columbia interior forest soils (Kishchuk 1998).

Forest floors were not examined in detail, but observations at other ESSF sites in the northern wet belt indicate that mesic sites are dominated by Hemimors and Humimors (P. Sanborn and R. Trowbridge, unpublished soil descriptions, 1999), which differ in their relative proportions of F and H horizons (Green et al. 1993). The relatively thin forest floors, compared to those in adjacent ICH ecosystems at lower elevation, likely reflects a lower rate of litter input in less productive subalpine forests.

TABLE A1 *Morphological description of Orthic Humo-Ferric Podzolic pedon, Lucille Mountain (Sanborn, unpublished field notes, 1995)*

Horizon	Depth (cm)	Description
LFH	0–3	Dark brown (7.5YR 3/2 m); semi-decomposed and humified needle litter and *Rhododendron* leaves; 2–4 cm thick; extremely acid.
Ae	0–4	Greyish brown (10YR 5/2 m); silt loam; weak, fine platy; very friable; plentiful very fine, fine, and medium roots; 25% angular and flat gravels and cobbles; abrupt, wavy boundary; 3–7 cm thick; extremely acid.
Bf1	4–11	Dark brown (7.5YR 3/3 m); silt loam; weak, fine and medium subangular blocky; friable; common fine and medium roots; 25–35% angular and flat gravels and cobbles; clear, wavy boundary; 4–8 cm thick; extremely acid.
Bf2	11–25	Dark brown (7.5YR 4/4 m); silt loam; weak medium subangular blocky; friable; few fine and medium roots; 30–40% angular and flat gravels and cobbles; gradual, wavy boundary; 8–18 cm thick; extremely acid.
Bf3	25–60	Yellowish brown (10YR 5/4 m); silt loam; massive; friable; few medium roots; 30–40% angular and flat gravels and cobbles; gradual, wavy boundary; 25–40 cm thick; extremely acid.
BC	60–100	Olive brown (2.5Y 4/4 m); sandy loam; massive; firm; 40% angular and flat gravels and cobbles; gradual, wavy boundary; 30–45 cm thick; extremely acid.
C	100–120+	Light olive brown (2.5Y 5/4 m); sandy loam; massive; firm; 40% angular and flat gravels and cobbles; extremely acid.

TABLE A2 *Physical and chemical properties of Orthic Humo-Ferric Podzolic pedon, Lucille Mountain (see Arocena and Sanborn 1999 for description of analytical methods)*

Horizon	Depth (cm)	Sand (g/kg)	Clay (g/kg)	C (g/kg)	N (g/kg)	Al_p[a] (g/kg)	Fe_p[a] (g/kg)	pH (H_2O)	pH ($CaCl_2$)	Avail P (mg/kg)	S (mg/kg)	K (cmol$_c$/kg)	Ca (cmol$_c$/kg)	Mg (cmol$_c$/kg)	Na (cmol$_c$/kg)	CEC[b] (cmol$_c$/kg)
LF	3–0	*n.d.*	*n.d.*	515.9	18.6	*n.d.*	*n.d.*	3.7	3.2	75.6	1711	2.44	9.08	5.35	0.49	20.33
Ae	0–4	388	45	9.7	0.9	0.78	0.57	3.8	3.1	2.5	27	0.05	0.24	0.21	0.04	3.66
Bf1	4–11	438	44	19.1	1.2	2.08	9.00	4.2	3.6	8.7	108	0.05	0.26	0.16	0.05	3.72
Bf2	11–25	399	41	10.2	0.9	2.42	8.39	4.5	3.9	2.3	54	0.02	0.12	0.05	0.04	1.56
Bf3	25–60	389	81	6.6	0.7	2.01	4.78	4.6	4.1	3.5	54	0.02	0.06	0.02	0.03	0.85
BC	60–100	574	45	2.7	0.4	1.20	1.95	5.0	4.4	9.5	33	0.05	0.15	0.07	0.06	0.69
C	100–120+	513	63	1.8	0.4	1.09	1.10	5.0	4.5	21.9	13	0.03	0.06	0.02	0.08	0.35

[a] *Al_p and Fe_p = pyrophosphate-extractable Al and Fe.*
[b] *CEC = cation exchange capacity.*

TABLE A3 *Summary of 1992 post-harvest live-tree residual basal area and diameter distributions for the Lucille Mountain partial cut treatments*

	Group retention (GR)			Irregular shelterwood (IS)			Single-tree selection (ST)		
	Bl	Se	Total GR	Bl	Se	Total IS	Bl	Se	Total ST
Live tree basal area (m^2)	8.17	1.84	10.01	9.57	5.36	14.93	13.66	2.70	16.37
Dead tree basal area (m^2)	0.65	0.41	1.06	1.31	0.00	1.31	0.67	0.00	0.67
dbh distribution (sph)(5-cm classes)									
5	41.7	4.2	45.9	7.4	0.0	7.4	33.3	2.8	36.1
10	63.9	4.2	68.1	66.7	7.4	74.1	73.6	4.2	77.8
15	101.4	4.2	105.6	50.4	3.0	53.4	119.4	1.4	120.8
20	84.7	2.8	87.5	43.0	1.5	44.5	76.4	2.8	79.2
25	54.2	4.2	58.4	23.7	1.5	25.2	47.2	2.8	50.0
30	41.7	1.4	43.1	38.5	3.0	41.5	41.7	1.4	43.1
35	11.1	1.4	12.5	20.7	5.9	26.6	36.1	2.8	38.9
40	6.9	1.4	8.3	23.7	5.9	29.6	23.6	2.8	26.4
45	0.0	41.4	1.4	5.9	3.0	8.9	6.9	1.4	8.3
50	1.4	1.4	2.8	4.4	1.5	5.9	6.9	1.4	8.3
55	0.0	0.0	0.0	1.5	4.4	5.9	0.0	2.8	2.8
60	1.4	0.0	1.4	0.0	4.4	4.4	0.0	1.4	1.4
65	0.0	1.4	1.4	0.0	0.0	0.0	0.0	2.8	2.8
70	0.0	1.4	1.4	0.0	3.0	3.0	1.4	0.0	1.4
>72.5	0.0	0.0	0.0	0.0	1.5	1.5	1.4	0.0	1.4

General

DeLong, C., M. Osberg, D. Coopersmith, and W. Hays. 1991. Working Plan, EP 1119.01: Comparison of forest management techniques for high-elevation forests: Lucille Mountain Project. For. Sci. Sect., Prince George For. Reg., B.C. Min. For., 1011 4th Ave., Prince George, B.C. 32 pp.

Jull, M.J., C. DeLong, A.M. Eastham, R.M. Sagar, and S.K. Stevenson. 1996. Establishment Report for EP 1119: Comparison of forest management techniques and silvicultural systems for high-elevation ESSF forests. Silvicultural Systems Project SS014. Draft. For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., 1011 4th Avenue, Prince George, B.C. 58 pp.

Jull, M.J, C. Delong, A.M. Eastham, R.M. Sagar, S.K. Stevenson, and R.L. Delong. 1996. Testing silvicultural systems for the ESSF: early results of the Lucille Mountain Project. B.C. Min. For., Prince George For. Reg., For. Resour. and Practices Team. For. Res. Note #PG-01. 8 pp.

Climate

Pettersen, K.M. 1993. Edge effect on a high elevation clearcut. BSc (Honours) thesis. Univ. Victoria, Victoria, B.C. 83 pp.

Wind and windthrow

Fletcher, S. 1996. Examination of 1996 wind events and consequences on a high-elevation clearcut. Unpublished report. For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., 1011 4th Avenue, Prince George, B.C. 22 pp.

Stand history and development

Audet, C. 1992. Tree response to single-tree wind-fall gaps in the moist, mild Engelmann spruce-subalpine fir biogeoclimatic subzone: a study on Lucille Mountain, McBride, B.C. BScF thesis. Univ. B.C., Vancouver, B.C. 84 pp + app.

Arboreal lichens

Stevenson, S.K. 1993. Alternative silviculture systems to maintain caribou habitat: Lucille Mountain Project. Establishment Report. Unpubl. rep. prepared for BC Hydro, Mica Wildlife Compensation Program. Silvifauna Research, Prince George, B.C. 16 pp.

_____. 1997. Abundance of arboreal lichens before and after selection harvesting at Lucille Mountain 1989–1996. Unpubl. rep. prepared for For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., 1011 4th Avenue, Prince George, B.C. Silvifauna Research, Prince George, B.C. 19 pp. + figs.

_____. Growth rates of alectorioid lichens in partially cut and unharvested stands in central British Columbia. In prep.

Natural regeneration

Eastham, A.M. 1999. Natural regeneration sub-project 6-year results. Lucille Mountain EP 1119 ESSF Silvicultural Systems Study. Unpubl. report prepared for For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., 1011 4th Avenue, Prince George, B.C. Industrial Forestry Service, Prince George, B.C. 8 pp. + figs.

Eastham, A.M. and M.J. Jull. 1999. Factors affecting natural regeneration of *Abies lasiocarpa* and *Picea engelmannii* in a subalpine silvicultural systems trial. Can. J. For. Res. 29:1847–1855.

Planted regeneration

Lajzerowicz, C.C. 2000. How does overstory retention affect above- and below-ground resource availability and seedling performance? Implications for silvicultural systems choice in the ESSF. MSc thesis. Univ. North. B.C., Prince George, B.C. 78 pp.

Lajzerowicz, C.C., M.B. Walters, M.J. Jull, M. Krasowski, and H.B. Massicotte. Factors limiting growth of seedlings of *Picea engelmannii* and *Abies lasiocarpa* in a partial cut silvicultural systems trial in north-central British Columbia. In prep.

Other

Prescott, C.E. 1996. Modelling forest management effects on organic matter decomposition in British Columbia. *In* Forest management for bioenergy. Proceedings of a joint meeting of Activities 1.1, 1.2, and 4.2 of Task XII in Jyvaskyla, Finland, September 9th and 10th, 1996. The Finnish Forest Research Institute. Vantaa Research Centre. Research Papers 640, pp. 221–226.

Prescott, C.E., L.L. Blevins, and C.L. Staley. 2000. Effects of clear-cutting on decomposition rates of litter and forest floor in forests of British Columbia. Can. J. For. Res. 30:1–7.

Sanborn, P. 1994. High elevation legume screening trial: Lucille Mountain silvicultural systems project. Unpublished Working Plan/Establishment Report. For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., 1011 4th Avenue, Prince George, B.C. 5 pp. + figures.

REFERENCES

Agriculture Canada. 1992. Soil landscapes of Canada. British Columbia – South. Publication 5279/B. Ottawa, Ont.

Alexander, R.R. 1956. A comparision of growth and mortality following cutting in old-growth mountain spruce-fir stands. U.S. Dep. Agric. For. Serv., Fort Collins, Colo. Res. Note RM-20.

_____. 1969. Seedfall and establishment of Engelmann spruce in clearcut openings: a case history. U.S. Dep. Agric. For. Serv., Fort Collins, Colo. Res. Pap. RM-53.

_____. 1987. Ecology, silviculture and management of the Engelmann spruce-subalpine fir type in the central and southern Rocky Mountains. U.S. Dep. Agric. For. Serv. Agric. Handb. No. 659.

Alexander, R.R. and C.B. Edminster. 1983. Engelmann spruce seed dispersal in the central Rocky Mountains. U.S. Dep. Agric. For. Serv., Fort Collins, Colo. Res. Note RM-424.

Alexander, R.R. and O. Engelby. 1983. Engelmann spruce-subalpine fir. *In* Silvicultural systems for the major forest types of the United States. R.M. Burns (editor). U.S. Dep. Agric. For. Serv. Agric. Handb. 445, pp. 59–62.

Armleder, H.M. and S.K. Stevenson. 1995. Silviculture systems to maintain caribou habitat in managed forests. *In* Proc. innovative silviculture systems in boreal forests, Edmonton, Alta., 4-8 October 1994. C. Bamsey (editor). Can. For. Serv., IUFRO, Canada-Alberta Partnership Agreement in Forestry, pp. 83–87.

Armleder, H.M., S.K. Stevenson, and S.D. Walker. 1992. Estimating the abundance of arboreal forage lichens. B.C. Min. For., Land Manage. Handb. Field Guide Insert 7.

Arocena, J.M. and P. Sanborn. 1999. Mineralogy and genesis of selected soils and their implications for forest management in central and northeastern British Columbia. Can. J. Soil Sci. 79:571–592.

Audet, C. 1992. Tree response to single tree wind-fall gaps in the moist, mild Engelmann Spruce-Subalpine Fir biogeoclimatic subzone: a study on Lucille Mountain, McBride, B.C. BScF thesis. Univ. B.C., Vancouver, B.C.

Balisky, A.C. and P.J. Burton. 1995. Root-zone soil temperature variation associated with microsite characteristics in high elevation forest openings in the interior of British Columbia. Agric. For. Meteorol. 77:31–54.

Barnes, G.H. 1937. The development of uneven-aged stands of Engelmann spruce, and probable development after logging. For. Chron. 13:417–457.

Bauman, N.G. and E. Wegwitz. 1972. Needle rusts of the true firs in British Columbia. Can. For. Serv., Pac. For. Res. Cent. Forest Pest Leaflet 45.

Bergstrom, B.W. 1983. Growth response and stand management of the advance subalpine fir on diameter-limit cut stands in the Adams Lake area of the Kamloops Forest Region. BSF thesis. Univ. B.C., Vancouver, B.C.

Black, T.A., R.S. Adams, R.L. Fleming, N.R. Eldridge, W.R. Mitchell, and I.J. Simpson. 1991a. Effects of site preparation treatments on seedling survival and growth in the ESSF biogeoclimatic zone. For. Can. and B.C. Min. For., Pacific Forestry Centre, Victoria, B.C. FRDA Memo 177.

Black, T.A., R.S. Adams, R.L. Fleming, N.R. Eldridge, W.R. Mitchell, and I.J. Simpson. 1991b. Reducing summer frost injury to seedlings in the southern Interior – Project 3.02. For. Can. and B.C. Min. For., Pacific Forestry Centre, Victoria, B.C. FRDA Memo 181.

British Columbia Forest Productivity Council. 1990. Minimum standards for the establishment and remeasurement of permanent sample plots in British Columbia. B.C. Forest Productivity Council, c/o B.C. Min. For. Executive, 595 Pandora Avenue, Victoria, B.C. Unpubl. rep.

British Columbia Ministry of Forests. 1992. Group selection system for high elevation forests (ESSFwc3) to maintain caribou habitat in the Cariboo Forest Region: working plan. Cariboo Forest Region, Williams Lake, B.C.

_____. 1995a. Silvicultural systems guidebook. Forest Practices Code of British Columbia. Victoria, B.C.

_____. 1995b. Establishment to free-growing guidebook. Forest Practices Code of British Columbia. Victoria, B.C.

_____. 1995c. Hazard assessment keys for evaluating site sensitivity to soil degrading processes guidebook. Forest Practices Code of British Columbia. Victoria, B.C.

_____. 1996. Draft field guide insert for site identification and interpretation for the Rocky Mountain Trench. B.C. Min. For., Prince George For. Region, Prince George, B.C.

_____. 1997. Site index estimates for coniferous tree species in British Columbia. Victoria, B.C.

_____. 1998. Provincial digital biogeoclimatic subzone/variant map. Version 4. http://www.for.gov.bc.ca/research/becmaps/BECMAPS.HTM.

_____. 2000. Establishment to free-growing guidebook. Forest Practices Code of British Columbia. Victoria, B.C.

Burton, P.J. and S.G. Cumming. 1995. Potential effects of climatic change on some western Canadian forests, based on phenological enhancements to a patch model of forest succession. *In* Boreal forests and global change. M.J. Apps and D.T. Price (editors). International Boreal Forest Research Association Conference, Saskatoon, Sask., September 25–30, 1994. Water, Air and Soil Pollution 82:401–414.

Butt, G. 1990. Forest regeneration in the ESSFa subzone: a problem analysis. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Report 118.

Carter, G.A. and W.K. Smith. 1988. Microhabitat comparisons of transpiration and photosynthesis in three subalpine conifers. Can. J. Bot. 66:963–969.

Chapin F.S. 1983. Direct and indirect effects of temperature on arctic plants. Polar Biol. 2:47–52.

Chappell, H.N., C.E. Prescott and L. Vesterdal. 1999. Long-term effects of nitrogen fertilization on nitrogen availability in coastal Douglas-fir forest floors. Soil Sci. Am. J. 63:1448–1454.

Coates, K.D. 1997. Wind damage two years after partial-cutting of the Date Creek silvicultural systems study in the interior cedar-hemlock forests of northwestern British Columbia. Can. J. For. Res. 27:1695–1701.

Coates, K.D. and P.J. Burton. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 29:1374–1382.

Coates, K. D., W.H. Emmingham, and S.R. Radosevich. 1991. Conifer-seedling microclimate at different levels of herb and shrub cover in Rhododendron-Vaccinium-Menziesia community of south central British Columbia. Can. J. For. Res. 21:858–866.

Coates, K.D., S. Hauessler, S. Lindeburgh, R. Pojar, and A.J. Stock. 1994. Ecology and silviculture of Interior spruce in British Columbia. For. Can. and B.C. Min. For., Victoria. B.C. FRDA Report 220.

Coupé, R., A.C. Stewart, and B.M. Wikeem. 1991. Engelmann spruce-subalpine fir zone. *In* Ecosystems of British Columbia. D. Meidinger and J. Pojar (editors). B.C. Min. For., Victoria, B.C., pp. 223–236.

Dang, Q.L., V.J. Lieffers, and R.L. Rothwell. 1992. Effects of summer frosts and subsequent shade on foliage gas exchange in peatland tamarack and black spruce. Can. J. For. Res. 22:973–979.

DeLong, S.C. 1991. The light interception index: a potential tool for assisting in vegetation management decisions. Can. J. For. Res. 21:1037 1042.

DeLong, S.C., M. Osberg, D. Coopersmith, and W. Hays. 1991. Comparison of forest management techniques for high elevation forests: Lucille Mountain Project. For. Sci. Sect., B.C. Min. For., Prince George, B.C. Working Plan.

Delucia, E.H. 1986. Effect of low root temperature on net photosynthesis, stomatal conductance and carbohydrate concentration in Engelmann spruce (*Picea engelmanni* Parry ex. Engelm.) seedlings. Tree Physiol. 2:143–154.

Delucia, E.H. and W.K. Smith. 1987. Air and soil temperature limitations on photosynthesis in Engelmann spruce during summer. Can. J. For. Res. 17:527–533.

Eastham, A.M. and M.J. Jull. 1999. Factors affecting natural regeneration of *Abies lasiocarpa* and *Picea engelmannii* in a subalpine silvicultural systems trial. Can. J. For. Res. 29:1847–1855.

Elliot, K.J. and A.S. White. 1984. Effects of light, nitrogen, and phosphorus on red pine seedling growth and nutrient use efficiency. For. Sci. 40:47–58.

Farnden, C. 1994. Forest regeneration in the ESSF zone of north-central British Columbia. Nat. Resour. Can., Can. For. Serv., Victoria, B.C. Info. Rep. No. B.C.-X-351.

Feller, M. 1997. Regeneration of Engelmann spruce and subalpine fir from seed in ESSFwc2 forests. *In* Sicamous Creek Silvicultural Systems Project: workshop proceedings. C. Hollstedt and A. Vyse (editors). B.C. Min. For., Victoria, B.C. Work. Pap. 24, pp. 154–169.

Fieldler, C.E., W.W. McCaughey, and W.C. Schmidt. 1985. Natural regeneration in Intermountain spruce-fir forests—a gradual process. U.S. Dep. Agric. For. Serv., Ogden, Utah. Res. Pap. INT-343.

Fraser, A.R. and J.L. Alexander. 1949. The development of the spruce-balsam type in the Aleza Lake Experimental Forest. B.C. For. Serv., Dep. Lands and For., Victoria, B.C. Tech. Publ. T-32.

Glew, D.R. 1963. The results of stand treatment in the white spruce-alpine fir type of the Northern Interior of British Columbia. B.C. For. Serv., Dep. Lands, For. and Water Resour. For. Manage. Note No.1.

Green, R.N., R.L. Trowbridge, and K. Klinka. 1993. Towards a taxonomic classification of humus forms. For. Sci. Monogr. 29.

Greene, D.F. and E.A. Johnson. 1994. Estimating the mean annual seed production of trees. Ecology 75:642–647.

Greene, D.F., J.C. Zasada, L. Sirois, D. Kneeshaw, H. Morin, I. Charron, and M.-J. Simard. 1999. A review of the regeneration dynamics of North American boreal forest tree species. Can. J. For. Res. 29:824–839.

Groot, A. and D.W. Carlson. 1996. Influence of shelter on night temperatures, frost damage and bud break of white spruce seedlings. Can. J. For. Res. 26:1531–1538.

Herring, L.J. 1977. Studies of advance subalpine fir in the Kamloops Forest District. B.C. Min. For., Victoria, B.C. Res. Rep. No. 80.

Hollstedt, C. and A. Vyse (editors). 1997. Sicamous Creek Silvicultural Systems Project: workshop proceedings. B.C. Min. For., Victoria, B.C. Work. Pap. 24.

Huggard, D.J., W. Klenner, and A. Vyse. 1999. Windthrow following four harvest treatments in an Engelmann spruce-subalpine fir forest in southern interior British Columbia, Canada. Can. J. For. Res. 29:1547–1556.

Jordan, D.N. and W.K. Smith. 1995. Microclimate factors influencing the frequency and duration of growth season frost for subalpine plants. Agric. For. Meteorol. 77:17–30.

Jull, M., D. Coxson, S. Stevenson, D. Lousier, and M. Walters. 1998. Ecosystem dynamics and silviculture systems in Interior wet-belt ESSF and ICH forests: workshop proceedings. UNBC Press, Univ. North. B.C., Prince George, B.C.

Jull, M., C. DeLong, A. Eastham, R.M. Sagar, and S. Stevenson. 1996. Establishment Report for EP 1119: Comparison of forest management techniques and silvicultural systems for high-elevation ESSF forests. Silvicultural Systems Project SS014. For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., Prince George, B.C. Draft.

Jull, M., C. DeLong, A. Eastham, R.M. Sagar, S. Stevenson, and R.L. DeLong. 1996. Testing silvicultural systems for the ESSF: early results of the Lucille Mountain Project. For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., Prince George, B.C. Note PG-01.

Jull, M. and C. Farnden. In prep. Long-term stand development of uneven-aged old-growth and partial-cut spruce-subalpine fir forests at Aleza Lake, British Columbia, 1926-1995. Univ. North. B.C., Prince George, B.C. Unpublished manuscript (available from authors).

Jull, M., S. Stevenson, A. Eastham, and P. Sanborn. 2001. Northern Rockies Wetbelt ICH/ESSF Silvicultural Systems Research Project: working plan. Univ. North. B.C., Prince George, B.C. Unpublished manuscript (available from authors).

Kishchuk, B.E. 1998. Sulphur availability on interior lodgepole pine sites. PhD thesis. Univ. B.C., Vancouver, B.C.

Klinka, K., Q. Wang, R.E. Carter, and H.Y.H. Chen. 1996. Height growth-elevation relationships in subalpine forests of interior British Columbia. For. Chron. 72:193–198.

Kohm, K.A. and J.F. Franklin. 1997. Creating a forestry for the 21st century: the science of ecosystem management. Island Press, Washington, D.C.

Körner, C. 1998. A re-assessment of high elevation treeline positions and their explanation. Oecologia 115:445–459.

Langsaeter, A. 1941. Om tynning I enalderet gran-og furuskog (About thinning in even-aged stands of spruce, fir, and pine.) Meddel. f.d. Norske Skogforoksvesen 8:131–216.

Lajzerowicz, C.C. 2000. How does overstory retention affect above- and below-ground resource availability and seedling performance? Implications for silvicultural systems choice in the ESSF. MSc thesis. Univ. North. B.C., Prince George, B.C.

Lieffers, V.J., C. Messier, K.J. Stadt, F. Gendron, and P.G. Comeau. 1999. Predicting and managing light in the understory of boreal forests. Can. J. For. Res. 29(6):796–811.

Lopushinsky, W. and T.A. Max. 1990. Effect of soil temperature on root and shoot growth and budburst timing in conifer seedling transplants. New Forests 4:107–124.

Lundmark, T. and J.E. Hallgren. 1987. Effects of frost on shaded and exposed spruce and pine seedlings planted in the field. Can. J. For. Res. 17:1197–1207.

Mather, J. 1987. Assessment of silvicultural practices in the ESSF zone in the Kamloops Forest Region. B.C. Min. For., Kamloops For. Reg., Kamloops, B.C. Internal Res. Rep.

Matson, P.A. and R.D. Boone. 1984. Natural disturbance and nitrogen mineralization: waveform dieback of mountain hemlock in the Oregon Cascades. Ecology 65:1511–1516.

McCaughey, W.W., C.E. Fieldler, and W.C. Schmidt. 1991. Twenty-year natural regeneration following five silvicultural prescriptions in spruce-fir forest of the Intermountain West. U.S. Dep. Agric. For. Serv., Ogden, Utah. Res. Pap. INT-439.

McCaughey, W.W. and W.C. Schmidt. 1982. Understory tree release following harvest cutting in spruce-fir forests of the Intermountain West. U.S. Dep. Agric. For. Serv., Ogden, Utah. Res. Pap. INT-285.

McDonald, P.M. and C.S. Abbott. 1994. Seedfall, regeneration, and seedling development in group-selection openings. U.S. Dep. Agric. For. Serv., Albany, Calif. Res. Pap. PSW-RP-220.

Miller, J., D. DeLong, B. McLellan, and E. Terry. 1999. Partial cutting prescriptions for mountain caribou in the ESSF of southeastern British Columbia—a retrospective investigation. B.C. Min. For., Nelson, B.C. Unpublished FRBC Rep. KB 97 194.

Möller, C.M. 1947. The effect of thinning, age, and site on foliage, increment, and loss of dry matter. J. Forestry 45:393–404.

Murphy, B. and P.L. Jackson. 1997. Extreme value analysis: return periods of severe wind events in the Central Interior of British Columbia. Unpubl. Univ. North. B.C. Interim Rep. to McGregor Model Forest Assoc., Prince George, B.C.

Newsome, T.A., M.J. Waterhouse, H.M. Armleder, and O.A. Steen. 2000. We're harvesting timber and maintaining caribou habitat: what about silviculture and other concerns? *In* From science to management and back: a science forum for southern interior ecosystems of British Columbia. C. Hollstedt, K. Sutherland, and T. Innes (editors). South. Interior For. Exten. and Res. Partnership, Kamloops, B.C., pp. 49–53.

Nyberg, B. 1998. Statistics and the practice of adaptive management. *In* Statistical methods for adaptive management studies. V. Sit and B. Taylor (editors). B.C. Min. For., Victoria, B.C. Land Manage. Handb. 42.

Oliver, C.D. and B.C. Larson. 1982. Stand development: its uses and methods of study. *In*: Forest succession and stand development research in the Pacific Northwest. J.E. Means (editor). OSU Press, Corvallis, Oreg., pp. 100–102.

Pacala, S.W., C.D. Canham, J.A. Silander, and R.K. Kobe. 1994. Sapling growth as a function of resources in a northern temperate forest. Can. J. For. Res. 24(11): 2172–2183.

Pettersen, K.M. 1995. Edge effect on a high elevation clearcut. BSc thesis. Univ. Victoria, Victoria, B.C.

Pickett, S.T.A. 1987. Space-for-time substitution as an alternative to long-term studies. *In* Long-term studies in ecology - approaches and alternatives. G.E. Likens (editor). Papers from the 2nd Cary Conference, May 13, 1987, Millbrook, N.Y.

Piene, H. and K. Van Cleve. 1978. Weight loss of litter and cellulose bags in a thinned white spruce forest in interior Alaska. Can. J. For. Res. 8:42–46.

Prescott, C.E., L.L. Blevins, and C.L. Staley. 2000. Effects of clear-cutting on decomposition rates of litter and forest floor in forests of British Columbia. Can. J. For. Res. 30:1–7.

Pojar, J. and D. Meidinger. 1991. British Columbia: the environmental setting. *In* Ecosystems of British Columbia. D. Meidinger and J. Pojar (editors). B.C. Min. For., Victoria, B.C., pp. 39–68.

Reynolds, G. 1997. Climatic data summary for the biogeoclimatic zones of British Columbia. B.C. Min. For. Res. Br., Victoria, B.C. Unpubl. rep.

Roe, A.L. and G.M. DeJarnette. 1965. Results of regeneration cutting in a spruce-subalpine fir stand. U.S. Dep. Agric. For. Serv., Ogden, Utah. Res. Pap. INT-17.

Rominger, E.M., L. Allen-Johnson, and J.L. Oldemeyer. 1994. Arboreal lichen in uncut and partially cut subalpine fir stands in woodland caribou habitat, northern Idaho and southeastern British Columbia. For. Ecol. Manage. 70:195–202.

Rominger, E.M., C.T. Robbins, and M.A. Evans. 1996. Winter foraging ecology of woodland caribou in northeastern Washington. J. Wildl. Manage. 60:719–728.

Smith, D.M. 1986. The practice of silviculture. 2nd ed. McGraw-Hill, New York, N.Y.

Smith, W.K. 1985. Western montane forests. *in* Physiological ecology of North American plant communities. B.F. Chabot and A.H. Mooney (editors). Chapman and Hall, New York, N.Y.

Soil Classification Working Group. 1998. The Canadian System of Soil Classification. Agric. and Agri-Food Can., Ottawa, Ont. Publ. No. 1646 (Revised).

Stathers, R.J. 1989. Summer frost in young forest plantations. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Report No. 073.

_____. 2001. Group selection systems for high elevation ESSFwc3 forests to maintain caribou habitat in the Cariboo Forest Region: microclimate studies. B.C. Min. For., Cariboo Forest Region. Williams Lake, B.C. Unpubl. contract rep.

Steen, O.A., R.J. Stathers, and R.A. Coupé. 1990. Identification and management of summer frost-prone sites in the Cariboo Forest Region. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Report No. 157.

Stettler, R.F. 1958. Development of a residual stand of interior spruce-subalpine fir during the first twenty-eight years following cutting to a 12-inch-diameter limit. B.C. For. Serv., Dep. Lands and For., Victoria, B.C. Res. Note 34.

Stevenson, S.K. 1997. Abundance of arboreal lichens before and after selection harvesting at Lucille Mountain 1989-1996. Unpubl. rep. prepared for For. Resour. and Practices Team, Prince George For. Reg., B.C. Min. For., Prince George, B.C. Silvifauna Research, Prince George, B.C.

Stevenson, S.K. In prep. Growth rates of alectorioid lichens in partially cut and unharvested stands in central British Columbia. Silvifauna Research, Prince George, B.C.

Stevenson, S.K., H.M. Armleder, M.J. Jull, D.G. King, B.N. McLellan, and D. Coxson. [2001]. Mountain caribou in managed forests: recommendations for managers. 2nd ed. B.C. Min. Environ., Lands and Parks. Wildlife Rep. No. R-26. In press.

Stevenson, S.K., H.M. Armleder, M.J. Jull, D.G. King, E.L. Terry, G.S. Watts, B.N. McLellan, and K.N. Child. 1994. Mountain caribou in managed forests: preliminary recommendations from managers. Technical Working Group for Mountain Caribou in Managed Forests (MCMF) Program. Res. Branch, B.C. Min. For., Victoria, B.C.

Stevenson, S.K. and K.A. Enns. 1993. Quantifying arboreal lichens for habitat management: a review of methods. B.C. Min. For., Victoria B.C. IWIFR-42.

Stevenson, S.K., M.J. Jull, and R.M. Sagar. 1999. Selection silvicultural systems in mountain caribou habitat: logging and learning at Pinkerton Mountain. B.C. Min. For., Prince George For. Reg., Prince George, B.C. For. Res. Note No. PG-19.

Sutherland, C., O. Steen, T. Newsome, J. Perry, P. Teti, B. Chapman, and H. Armleder. 1992. Group selection system for high elevation forests (ESSFwc3) to maintain caribou habitat in the Cariboo Forest Region. Working Plan. B.C. Min. For., Williams Lake, B.C. EP 1104.02.

Tranquillini, W. 1979. Physiological ecology of the alpine timberline. Ecological Studies 31. Springer-Verlag, New York, N.Y.

Vyse, A. 1997. The Sicamous Creek Silvicultural Systems Project: how the project came to be and what it aims to accomplish. *In* Sicamous Creek Silvicultural Systems Project: workshop proceedings. C. Hollstedt and A. Vyse (editors). B.C. Min. For., Victoria, B.C. Work. Pap. 24, pp. 4–14.

Wallace, J.M. and P.V. Hobbs. 1977. Atmospheric science: an introductory survey. Academic Press, New York, N.Y.

Waring, R.H. 1985. Carbon uptake and allocation in subalpine ecosystems as a key to management. Proc. IUFRO workshop: ecology of subalpine zones. Aug. 2-3, 1982. Oreg. State Univ., Corvallis, Oreg.

Weetman, G.F. 1965. The decomposition of confined black spruce needles on the forest floor. Pulp Pap. Res. Inst. Can. Woodlands Res. No. 165.

_____. 1996. Are European silvicultural systems and precedents useful for British Columbia silvicultural prescriptions? For. Can. and B.C. Min. For., Victoria, B.C. FRDA Report 239.

Weetman, G.F. and A. Vyse. 1990. Natural regeneration. *In* Regenerationg British Columbia's forests. D.P. Lavender, R. Parish, C.M. Johnson, G. Montgomery, A. Vyse, R. Willis, and D. Winston (editors). Univ. B.C. Press, Vancouver, B.C., pp. 118–130.

Will, G.M., P.D. Hodgkiss, and H.A.I. Madgwick. 1983. Nutrient losses from litterbags containing *Pinus radiata* litter: influences of thinning, clearfelling and urea fertiliser. N. Z. J. For. Sci. 13:291–304.

Wright, E.E., K.D. Coates, C.D. Canham, and P. Bartemucci. 1998. Species variability in growth response to light across climatic regions in northwestern British Columbia, Canada. Can. J. For. Res. 28:871–886.

Yin, X., J.A. Perry, and R.K. Dixon. 1989. Influence of canopy removal on oak forest floor decomposition. Can. J. For. Res. 19:204–214.

Youngblood, A.P. 1990. Effect of shelterwood removal methods on established regeneration in an Alaska white spruce stand. Can. J. For. Res. 20(9):1378–1381.

Zak, D.R., D. Tilman, R.R Parmenter, C.W. Rice, F.M. Fisher, J. Voce, D. Milchunas, and C.W. Martin. 1994. Plant-production and soil microorganisms in late-successional ecosystems—a continental-scale study. Ecology 75:2333–2347.